Ontology based Semantic Engineering Framework and Tool for Reconfigurable Automation Systems Integration

by

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Declaration

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree.

The work presented (including data generated and data analysis) was carried out by the author.

.....(Signed)

Jiayi Zhang

.....(Date)

Abstract

Digital factory modelling based on virtual design and simulation is now emerging as a part of mainstream engineering activities, and it is typically geared towards reducing the product design cycle time. Reconfigurable manufacturing systems can benefit from reusing the existing knowledge in order to decrease the required skills and design time to launch new product generations. The various industrial simulation systems are currently integrating product design, matching processes and resource requirements to decrease the required skills and design time to launch new products.

However, the main focus of current reconfigurable manufacturing systems has been modular production lines to support different manufacturing tasks. Additionally, the design data is not transferrable from various domain-specific software to a collaborative and intelligent platform, which is required to capture and reuse design knowledge. Product design is still dependent on the knowledge of designers and does not link to the existing knowledge on processes and resources, which are in separate domains.

To address these issues, this research developed an integration method based on semantic technologies and product, process, resource and requirements (PPRR) ontologies called semantic-ontology engineering framework (SOEF). SOEF transferred original databases to an ontology-based automation data structure with a semantic analysis engine. A pre-defined semantic model is developed to recognise custom requirement and map existing knowledge with processing data in the automation assembly aspect.

The main research contribution is using semantic technology to process automation documentation and map semantic data to the PPRR ontology structure. Furthermore, this research also contributes to the automatic modification of system simulation based on custom requirements. The SOEF uses a JAVA-based command-line user interface to present semantic analysis results and import ontology outputs to the vueOne system simulation tool for system evaluation.

List of Publications

First Author

- Zhang, J., Ahmad, B., Vera, D., & Harrison, R. (2018, July). Automatic Data Representation Analysis for Reconfigurable Systems Integration. In 2018 IEEE 16th International Conference on Industrial Informatics (INDIN) (pp. 1033-1038). IEEE.

- Zhang, J., Ahmad, B., Vera, D., & Harrison, R. (2016, July). Ontology based semantic-predictive model for reconfigurable automation systems. In Industrial Informatics (INDIN), 2016 IEEE 14th International Conference on (pp. 1094-1099). IEEE.

- Zhang, J., & Agyapong-Kodua, K. (2015, March). Cloud Based Semantic-Predictive Models for Enhanced Manufacturing Systems Performance. In 2015, Factory 2050 Conference.

- Zhang, J., & Agyapong-Kodua, K. (2015, May). Integrated Ontologies in Support of Factory Systems Design. In INCOM 2015, IFAC Symposium on Information Control in Manufacturing (pp.2175-2182).

- Zhang, J., & Agyapong-Kodua, K. (2015). Knowledge-Based Cloud Design Architecture for Intelligent Factory Systems. In NICSO 2015, Nature Inspired Cooperative Strategies for Optimization. Springer.

- Zhang, J., & Agyapong-Kodua, K., Semantic modelling for prediction of manufacturing systems behaviour at early design stage. Submitted to Computers in Industry, (September 2015).

- Zhang, J., & Lu, J. (2014, July). Using Mobile Serious Games for Learning Programming. In INFOCOMP 2014, The Fourth International Conference on Advanced Communications and Computation (pp. 24-29).

Co-Author

- Ferrer, B. R., Mohammed, W. M., Ahmad, M., Iarovyi, S., Zhang J., Harrison, R. & Lastra, J. L. M. "Comparing Ontologies and Databases: a critical review for lifecycle engineering models in manufacturing", Submitted to the Knowledge and Information Systems (August 2018).

- Shang, M., Agyapong-Kodua, K., Stavridis J., Zhang J., Asare K., Fysikopoulos A., Marine C. and Ceglarek D. “A Digital Verification and Validation Framework for New Product Introduction”. Submitted to the Research in engineering design (May 2018).

- Ahmad, M., Zhang, J., Ahmad, B., Harrison, R., “Connecting assembly process planning with machine control software using virtual engineering tools and semantic web technologies”, Submitted to the International Journal of Production Research (November 2017).

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Abbreviations and Acronyms

API	application programming interfaces
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CAPP	Computer-Aided Process Planning
CBM	Cloud-Based Manufacturing
CCE	Core Component Editor
CIM	Computer-Integrated Manufacturing
CLI	Command-Line Interface
CNC	Computer Numerical Control
CoTS	Commercial-of-The-Shelf
DES	Discrete Event Simulation
DF	Digital Factory
DFA	Design for Assembly
DFDR	Design for Disassembly and Recyclability
DFE	Design for Environment
DFM	Design for Manufacture
DFMA	Design for Manufacture and Assembly
DFMT	Design for Maintainability
DFQ	Design for Quality
DFX	Design for X
DIK	Data-Information-Knowledge
EVs	Electric Vehicles
FMS	Flexible Manufacturing System

GATE	General Architecture for Text Engineering
GUI	Graphical User Interface
HIP	Human Information Processing
HMI	Human–Machine Interface
IDA	Institute for Defence Analyses
JAPE	Java Annotation Pattern Engine
KB	Knowledge Base
KDCM	Knowledge-Driven Configurable Manufacturing
MDA	Model-Driven Architecture
MDI	Model-Driven Interoperability
MLP	Make-Like-Production
NP	Noun Phrase
OEM	Original Equipment Manufacturer
OEMs	Original Equipment Manufacturers
OS	Operating System
OWL	Web Ontology Language
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
POS	Part-of-Speech
PPR	Product-Process-Resource
PPRR	Product-Process-Resource-Requirement
RDB	Relational Database
RDF	Resource Description Framework
RMS	Reconfigurable Manufacturing System
SMEs	Small and Medium sized Enterprises
SOEF	Semantic-Ontology Engineering Framework

SPARQL	SPARQL Protocol and RDF Query Language
SQL	Structured Query Language
SuFSeF	Sustainable Factory Semantic Framework
TOGAF	The Open Group’s Architecture Framework
VFDM	Virtual Factory Data Model
VFF	virtual factory framework
VP	Verb Phrase
XML	Extensible Markup Language

CHAPTER 1 **INTRODUCTION**

The capability of reconfiguration support is becoming a key competitive indicator for current automation systems within large enterprises, due to increasing product variety and complexity (Elmaraghy and Elmaraghy, 2016). Additionally, the demand for agility and cost-effectiveness in high-volume manufacturing systems is requiring production companies to improve production line flexibility and reduce the product life-cycle time from design to production (Thompson et al., 2018, Kiefer et al., 2017). However, for a large number of customised product, frequent product changes and complex production systems present massive challenges to engineers within the manufacturing industry, as it is difficult to assign the product information to a specific product accurately and this often causes engineers misunderstanding throughout the workflow (Durkop et al., 2014).

In particular, the possibilities for individual requirements have increased dramatically through the ever-growing application of information technologies, including semantic technology (Asmae et al., 2017, Yang et al., 2012). As Figure 1-1 shows, diverse mindsets and varied personal preferences are driving the demand for the production of customised products. However, current manufacturing systems are no longer capable of fulfilling the growing needs of customers with individualised product requirements (Srinivasan et al., 2018). To solve this issue, companies have invested hugely in modern information technology. For example the World Wide Web, mobile technology, and smart production lines. However, to enable companies to achieve product uniqueness whilst at the same time maximising manufacturing capabilities in the production line, they need to be able to apply the specific product-driven changes during their manufacturing systems upgrades (Maganha et al., 2018).

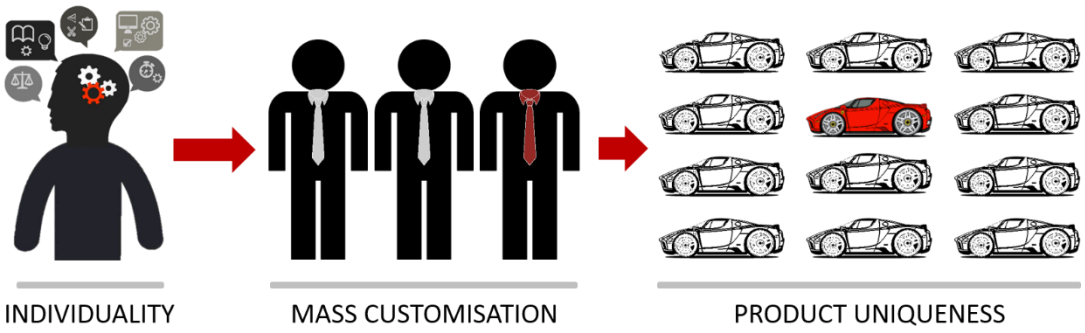


Figure 1-1 From Independent Requirement to Product Uniqueness

The established engineering approach now typically includes methodology, modelling and design, which covers the entire product lifecycle. However, it is not adequately meeting the requirements of product lifecycle management (Demoly et al., 2013). To change the existing manufacturing process and design, a business would need to recruit groups of experienced engineers and diverse resources (Andersen et al., 2016). Additionally, updating highly complex systems may cause unpredictable conflicts among different manufacturing systems (Puik et al., 2016). Hence, many researchers tried to tackle this problem by using some proposed form of reconfigurable manufacturing system (Rösiö et al., 2019). Such reconfigurable manufacturing systems could efficiently re-use the existing knowledge in order to decrease the required skills and design time to launch new products.

Due to frequent changes in product uniqueness, the challenge faced by reconfigurable manufacturing systems is to meet ever-changing production requirements whilst maintaining production capacity and quality. Product upgrades lead to amendments in the production line and even the abandonment of the previous production line, to meet the needs of new products. Any change in the production line could affect system operation, increase the product lifecycle time, and have financial costs. Another significant problem is that these changes cannot be achieved in one loop, because the product, process, mechanical and control engineers need to carry out a number of design change loops in order to finalise the new product and manufacturing system design.

Dombrowski et al. (2014) stated that product design time is wasted during process development and more than 70% of wasted time is caused by design

decisions. As a consequence, this research can save 50% of product design time for process planning, resource selection using ontology-based semantic engineering framework. At the same time, the ontology-based semantic method has been applied to a political case study to evaluate the influence of authoritarian media (Russia Today) for the US 2016 election. Based on the emotional analysis of online videos, authors found that Hillary Clinton is the most covered political candidate, albeit in a negative tone. Bernie Sanders and Trump, in contrast, received less coverage yet with positive tones. Nevertheless, Russia Today refuted that Russia's interference of the US election is a conspiracy.

1.1 Reconfigurable Manufacturing System

1.1.1 Requirement of Reconfigurable Manufacturing System

Today a diversity of products need to be produced at high volume and with flexibility. Traditional production lines are currently facing a big challenge of adapting to the variations of different markets' requirements, which is driving a need for rapid manufacturing changes. Customer requirements are not only amending the basic characteristics of the product like the form and colours but also necessitating upgrading the product technology and creative ideas. As highly integrated components are assembled into a limited space, so intelligent hardware and software interactions have to be upgraded to improve the production line performance. In addition, advanced products demand better mechanical and electrical systems and software development. Customisation is continuously challenging the large-scale production model to be able to meet a large variety of customers' demands. Product diversity often directly leads to increased product complexity and declining production volumes. In this environment, manufacturers may find it difficult to keep costs within an acceptable level and to avoid losing competitiveness.

Introducing automation to a production line can offer the potential to improve product quality, output and traceability. However, the integrated production process is an extremely complex one, which involves a collaboration of many different departments and engineers. Figure 1-2 states a typical manufacturing production flow based on product requirements and extra requirements. At the early design stage, product requirements are delivered to product designers for

product design. After that, the product draft is evaluated by process engineers and manufacturing engineers for process planning and assembly checks. If any feature does not fulfil the process requirements or resource availability, the product has to be redesigned and then reviewed for physical system development. However, product design may also be changed by new product requirements. Thus, all the above steps will be started for the next product lifecycle. In the normal production processes, product lifecycle will be determined by the complexity of the automated production system. The increase in participants and information exchange time will also potentially increase the risk of new product delays and production mistakes.

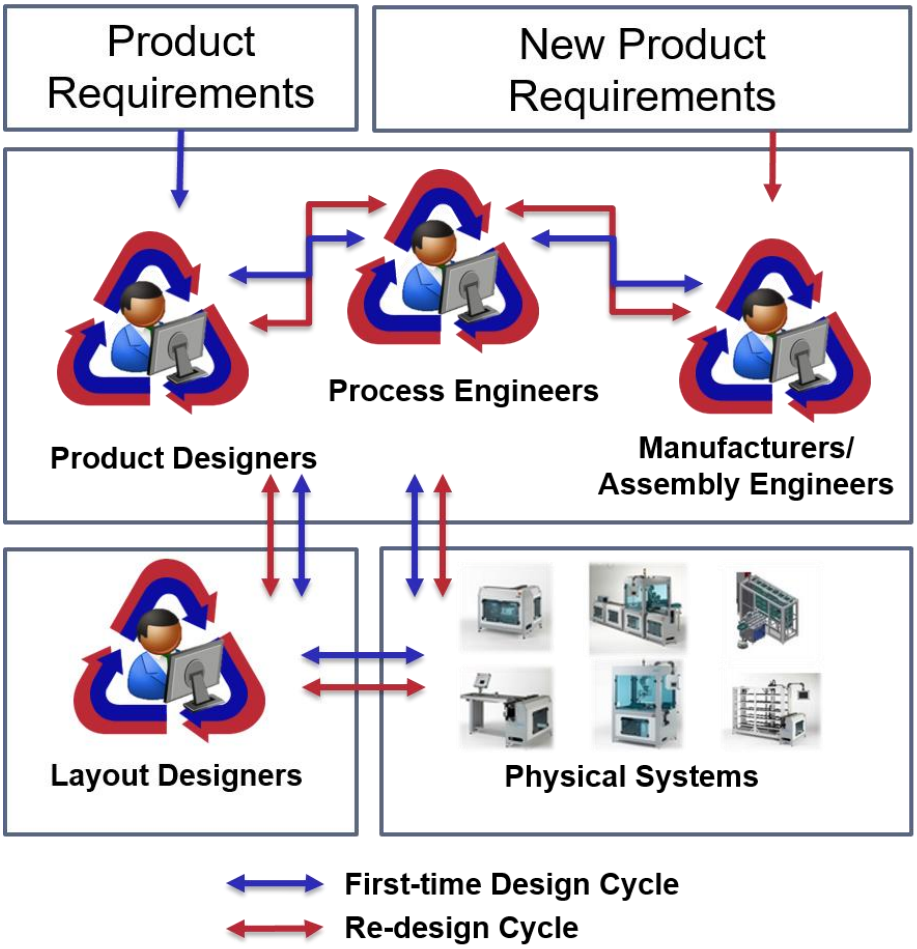


Figure 1-2 Manufacturing Systems Processes

Effective delivery of information and high-speed data transportation are the infrastructures of industrial automation systems. Apart from that, production processes remain isolated and unconnected by certain engineers or managers

at each stage. Therefore, existing data integration models can be modified by improving product development processes. Based on Figure 1-2, manufacturing systems processes can be summarised as the following steps:

The first step in product development is a prototype design that is based on product requirements. Product 3D modelling is constantly refined and upgraded by product engineers. Meanwhile, process methodology and assembly sequences are taken into consideration at product design, but typically only via the application of their limited process and resource knowledge.

Following this, the product design will be delivered to process engineers to undertake detailed process planning. Based on the manufacturing process knowledge, process plans then can be generated from product design details including process capabilities, cycle time and related resourcing. However, adequate information exchange demands frequent communication between product engineers and process engineers. Sometimes, product design will be changed because of process requirements or limitations.

Furthermore, manufacturing engineers are subsequently responsible for translating the process planning sheet into a machine-readable language to running process sequence on the production line. Product and process requirements also need to be approved by assembly engineers, but they might also need to modify the product design due to the unavailability of suitable resources. After production finalisation, mechanical engineers may need to (re)arrange the automation process and then enable layout engineers to install the physical systems in a suitable way within the factory.

Finally, control engineers can complete the PLC code development and deploy the necessary process logic with the required sequence and interlock conditions. If all goes too smoothly, new products will hence be produced by product development, process planning and resource assembly. However, additional requirements may well make it necessary to repeat the development loops across product, process and resource domains.

1.1.2 Current Solutions

Flexibility and reconfigurability require of changing of both hardware and software throughout the system and modular design concepts are widely to be used to enable quick changes in both software and hardware (Brusaferri et al., 2014, Yousuf and Gordon-Ross, 2016). For example, modular processing stations have a common input and output connectors based on standard specifications. Typically, modules are designed to perform a specific task autonomously but can be integrated with other modules in various configurations, in a plug & play manner to perform the manufacturing process.

Hence, a manufacturing line can be configured by a combination of interacting modules, but each of the modules would provide specific functions or services. All the possible combinations of these actions and services represent the capability of this manufacturing line. Any future requirement could potentially be achieved by adding new modules or reconfiguring existing actions or services. Where necessary, modules can be swapped or upgraded to enable the manufacture of new products. Additionally, modular resources could reduce the cost of maintenance and upgrade.

However, there are still a number of issues that need to be addressed. For example, an appropriate granularity of modules will improve the automation system performance. Excessive granularity in production lines will result in a large number of control interfaces, which increase the complexity of mechanical, control and software system, as well as the costs of maintenance and upgrade (Cavin and Lohse, 2014). Therefore, the integrity of the reconfigurable manufacturing system (RMS) relies on a stable and reliable integration strategy.

Automation system integration can represent a set of modules, which connect to an information, mechanical and control interface that can communicate and integrate with different automation systems. Corresponding machine modules can be combined to perform a series of operations, which match the characteristics of the product parts and achieve the required product-process-resource integration (Cutting-Decelle et al., 2007). In an assembly shop, different modular machines (e.g., swivel arms, distribution stations and gantries) can be

combined to build up a reconfigurable system for the part transport and assembly to suit a given task. Rule-based reconfigurable system will then be assisted in manufacturing system design and reconstruction. Additionally, intelligent industrial control systems can be implemented via integrated machine controllers.

Flexibility in a manufacturing system can be embodied in a variety of forms. For a given product family, customised-flexibility rather than a general-purpose flexible manufacturing system is often more appropriate. Thus, the reconfigurable manufacturing system has tremendous potential, compared with fully flexible systems, as it has the potential to minimise the cost of the product life-cycle. Furthermore, the reconfigurable system normally would be applied in designing a set of products rather than a part of the product. For example, Jaguar Land Rover Engine Manufacturing Centre required design and production of a range of different types of engines, so they need to test and adjust existing production lines to enable many different production engine characteristics. Consequently, most of the products in reconfigurable manufacturing systems would possess similar geometric features at the same level of tolerances and product cost. In the same way, the majority of the automation system resources should have the capabilities to produce all the parts of the given product families. However, traditional reconfigurable manufacturing systems still need to analyse all dominant features for product families and then to be customised in the characteristic of required process operations. To improve production flexibility, the same production equipment would need to be applied with different production tools to drive production efficiency and reduce manufacturing costs. However, it could be a challenge of using efficient production tools in automatic reconfiguration.

An intelligent reconfigurable system also includes a software platform to enable the design of the production system hardware and software, which can support process design and hardware planning before physical build. In fact, product, process, mechanical and control engineers need to participate in a number of design change loops to finalise product and manufacturing system design. In order to reduce the market launch-time and potential risks, a number of digital modelling and simulation tools are being adopted by industry, which can help

visualise, validate and optimise the manufacturing system. However, these tools make it difficult to reuse of existing knowledge and data from the product, process and resource domain due to the lack of strong data coupling. Although some software application can share editable resources, the details might still be lost during the data conversion. Typically, a huge amount of data cannot be shared and transferred across different systems and this results in the use of labour-intensive and ad-hoc methods of data sharing across different engineering domains (Wasmer et al., 2011).

1.2 Research Background

A manufacturing system should be flexible, reconfigurable, scalable and knowledge-based (KB), in order to produce multiple products with minimum costs (Zainol et al., 2013). To meet these requirements, intelligent data models need to support and formalise the integration of heterogeneous life cycle data, and to enable the manufacturing systems performance prediction at an early stage of the design cycle. After achieving this in a systematic way, it will then require the design and development of ontology methods and techniques to contain semantic contents (Agyapong-Kodua et al., 2013).

Many previous studies reported the increasing use of data modelling tools to enable reuse of data across different engineering domains. However, knowledge management and reuse in a systematic manner still not in place to support manufacturing systems reconfiguration with product requirements change (Koren and Shpitalni, 2010). Therefore, the modification of simulation models to accommodate changes can result in a significant cost and is time-consuming, as substantial knowledge and experience are required to understand the interdependency of product, process and resource changes for system reconfiguration (Wagner et al., 2014). Additionally, the existing digital modelling tools are far too complex to use, as they require a wide range of technical skills and significant manual work.

1.2.1 Process Planning

Process planning is a key step to combine product and resource in the product life cycle, which also links with manufacturing process design. Because process

planning provides all manufacturing process information including products and parts information for the process, resource capabilities and process command (Yang et al., 2016). Typically, products and parts information contain characteristics of products dimension and elements, which is related to process steps and control logic parameters. Furthermore, all associated resources should be involved in process planning to provide a manufacturing availability report for future process evaluation. Thus, comprehensive process planning can be used for manufacturing process modelling to evaluate the functionality of the manufacturing process system. However, indispensable product manufacturing information models mainly focus on the single information domain and there is a lack of a systemic integration platform that can combine all information from a different domain.

To address the above problems, some existing solutions reported in the literature have relied on web-based collaborative systems, to help engineers exchange design knowledge and relevant information at the manufacturing system level. However, after reviewing the current integrating methodology, the integration of process planning is always slow while knowledge was recognising and exchanging. Practically, Original Equipment Manufacturers (OEM) usually require their Tier 1 and Tier 2 suppliers to add their components' information to produce the ultimate product in the market. Thus, distributed manufacturing relies on different manufacturers and OEMs will deal specifically with planning and assembly work. As manufacturing becomes increasingly globalised, it is essential to communicate effectively and to coordinate the sharing of information related to products, process and resources across manufacturers.

Computer-aided process planning (CAPP) with computer-aided design (CAD) and computer-aided manufacturing (CAM) reducing the difficulties of product manufacturing, because CAPP helps engineers to design a planning process of designed elements and product sets. However, working via intelligent modelling tools like DELMIA, CATIA, the engineers need to have profound skills in process development as well as product and resource knowledge (Roj, 2014). In addition, process planning needs to be integrated with different production systems including a set of processing equipment, handling system and operators (Zhu et

al., 2017). Hence, a process designer will have to consider all relevant manufacturing factors and variables for production process that deter the reconfigurable capacity of the entire production line and a large part of the production costs during the product life cycle.

In current manufacturing enterprises, one product can be produced through different production lines to achieve the same technical demand, and one production line could produce different products via changing process sequence. Furthermore, one processing chain of the manufacturing system is presented by a set of production processes, different automation equipment, various controlling systems and the human resources (Zhu et al., 2017). To optimise the production process and identify the production system performance, engineers would evaluate different manufacturing systems with process capabilities, resource capacities and competences. Although the decision-making process has been widely implemented in modern manufacturing system, most of the existing tools are concerned at process sequencing and process optimization levels. Implementing process planning for manufacturing system level is still extremely limited on the existing platforms, which are designed by different companies. Additionally, due to the diversity of production features, complex production process and uncertain production conditions, the decision-making process requires stronger informatics support and practice platform.

Process planning is one of the most important tasks in collaborative product development of a distributed environment, which involves different manufacturers in process scheduling. CAPP can record and optimise process information with related product and resources. By analysing engineering CAD module and resources, CAPP could automatically set technical parameters as resource input to recognise and decide manufacturing processes, as well as operations and resources of implementation of production. Moreover, knowledge-based architecture is integrated into the existing CAPP software to improve the decision-making process. However, the integration of entire manufacturing knowledge (including process flow, product features, and resource capabilities) is very tough for current CAPP. All the data usually are scattered in different domain software or even just used by different professional engineers. Internet and cyber-physical

systems have been developed for cross-platforms and manufacturing to adapt the network-based manufacturing system changes. To improve the competitiveness of manufacturing enterprises and accelerate the speed of new products development, information integration in different areas is an irreversible trend for the process planning models. Therefore, suppliers and business partners participated in the network should also consider system integration. All participants should build an infrastructure for information, including design details, process planning and resource management to enhance CAPP's capabilities. With the upgrading of hardware technology and software representations, some new product concepts have been introduced for process planning, such as Cloud Automation System (CAS). However, the increasing numbers of production models and processes are slowing down the product processes integration, because of the increased complexity of the different processes. The integration of product resource and process knowledge heavily depends on the CAD/CAM/CAPP system sharing abilities.

1.2.2 System Simulation

System simulation can enrich a process design and provide a wealth of visual information for manufacturing processing (Ruiz et al., 2014). It significantly reduces the manufacturing risk from design to process operation. Design and process mistakes are usually fixed in the early product design phase, so the manufacturing industry has been widely used system simulation technology to improve production efficiency and reduce production costs.

In order to apply for Knowledge-Driven Reconfigurable Manufacturing (KDCM) system, the system simulation tools have been introduced the concepts of subclasses and distributed workstations (Ferrer et al., 2015b). However, they cannot automatically match and reconfigure related processes and station to increase the flexibility of system simulation. Although many simulation tools are focusing on process scheduling and system presentation, the scheduling models are limited to static settings rather than real-time configuration. Some of the advanced system simulation tools will allow users to pre-set the system to optimise the static model before the physical system running. Real-time scheduling management and real-world interrupted are not implemented in

existing system simulation tools. In terms of product customisation and manufacturing requirements updated, system simulation tools have to adapt to these changes and then control the costs of iteration to meet the market requirements. Thus, the rapid response system simulation tools will be requested for the manufacturing modifications in real-time processing. Current system simulation tools require an intelligent resource management platform, which has all available resource information together with the corresponding capabilities in the production workshop. After analysing the existing production capacity models, the system simulation tool will automatically combine all available resources to complete product and process tasks. Although the tools in the workshop are known, the production capacity and reconfigurable flexibility are not automatically summarised by the manufacturing system. Once the details of the product have been changed, current system simulator cannot make the appropriate adjustments like parts routing, the sequence of production, and the resources.

1.2.3 Virtual Engineering

Rapid hardware design tends to be more common, due to uncertain product requirements and customisations. Virtual prototyping will be more widely used in the hardware design field, to avoid unnecessary mistakes during system design (Ryan et al., 2016). However, the existing Virtual Prototyping Environment (VPE) is limited because of hardware systems complexity, such as Cooperative work robots, precision machining equipment, and quality inspection equipment. Moreover, large manufacturing systems might be difficult to be simulated to a real-time simulation solution under realistic conditions. VPE supports manufacturing engineers in improving the manufacture system's reusability, traceability and reconfigurability. However, VPE does not support automated design for testing and evaluation, but it focuses more on the system processes in virtual software simulation environments. Modular manufacturing system design and distribution control systems would be the flexible design techniques going forward. However, current VPE tools cannot simply support product lifecycle management of reconfigurable manufacturing systems. Hence, another requirement of VPE is adapting it in the new reconfigurable technology, which to improve the efficiency of system design and reduce cost.

Current VPEs are often customisable for different projects by using specific model technology (i.e. software modelling, data format, module service). This has massively increased the development and maintenance costs, as well as restricted information sharing between different industrial partners. A common virtual prototyping platform with flexible modelling is urgently required for rapid virtual engineering to react effectively to requirement or resources changes.

1.2.4 System Integration with Ontology

Modern industrial requirements need products to be made in the highest quality and function while performance is within acceptable limits. Also, there is an increase in product complexity and an intense market demand, which dictates a shorter development time. Thus, designers need enhanced information on product design processes, sales & marketing, remanufacturing and recycling, to be able to fully understand the interconnectivity of design decisions (Zhang et al., 2012). However, the request for addressing these demands has led to a plethora of digital modelling tools for industrial application (Bodein et al., 2014). This includes suites of tools of analysing complex product data flow together with diversified product structures. Typical examples are Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), Computer-Aided Process Planning (CAPP) and Computer-Integrated Manufacturing (CIM). With the well-defined cooperation of different systems, product development can be supported by step-based CAD/CAM/CNC factory scenarios (Campos and Miguez, 2011). However, the great challenge is data conversion between systems, since Original Equipment Manufacturers (OEMs), and their Tier 1 and 2 suppliers who are usually Small and Medium-sized Enterprises (SMEs) may use different applications (Aleixos et al., 2004). Previous research by Ihwan and Soonhung (2013) indicated that traditional step-based translation process from CAM data to CAE data can take about 14 days. There is also an additional risk of error accumulation when product models are converted in this way. As a result, the best performing industries currently are implementing the product-process-resource development platform for intelligent manufacturing design (Hao et al., 2014).

Although this is theoretically feasible, designers are frequently unable to fully access the relevant life cycle knowledge, due to a large number of distributed data sources and non-uniform Application Programming Interfaces (API). Many authors have confirmed that although data modelling tools are applied in many industries, knowledge management and their reuse have not been fully resolved in current manufacturing design systems. Furthermore, the Commercial-of-The-Shelf (CoTS) software which is attempting to address the above issue is expensive for SMEs and thus utilised only by major OEMs. The gap of accessing the required life cycle knowledge between OEMs and SMEs are thus further enlarged in this case (Tolio et al., 2013).

Designers must be enabled to benefit from the existing product, process and resource knowledge allow fast, iterative, development and the rapid digital prototyping of factories. Hence, knowledge-based information management has been considered as a core to the next generation of viable design techniques (Braglia et al., 2014). Knowledge-based systems have the tendency to support the integration of systems requirements, with perceived manufacturing systems solutions of first-hand resource analysis. To support the rapid selection of resource solutions, this thesis proposes an integrated ontology-based approach, which represents the product, process, and resource ontologies with useful first-hand design solutions.

Previous research in this direction has resulted in: (1) the development of conceptual ‘digital factory’ platforms (Stef et al., 2013); (2) data integration mechanisms (Romano, 2003, Ratchev et al., 2004); (3) new programming logics and knowledge-driven reconfigurable systems (Mehrabi et al., 2000, Raza and Harrison, 2011); (4) hardware and adaptive components (Philip et al., 2004, Tolio et al., 2010); (5) Plug and Produce Multi-Agent Environment (Ferber, 1999); (6) semantics architecture and modelling (Kantorovitch et al., 2008) and (7) collective systems adaptability based on swarm intelligence and other artificial intelligence techniques (Breslin et al., 2010). One of the major observations from the study of these previous research activities indicates that there is still a need for an appropriate contextual description of life cycle knowledge (ontology) and the better use of such integrated knowledge at the design stage (Agyapong-Kodua

et al., 2014a, Agyapong-Kodua et al., 2014b). Many practical challenges existing while implementing integrated ‘intra or inter information systems’ (Izza, 2009). This is because systems are commonly designed without detailed consideration of integration levels, but it is essential for enterprises though product-process-equipment interconnections, file transfers and data formats, as well as manipulations, specifications and representations levels.

Another challenge is that different product components are produced in various engineering environments, with a wide range of models, tools and processes that are not designed to operate seamlessly together (Moser and Biffl, 2012). However, there is limited intelligence in the current product design lifecycle management systems, because process and resources changes cannot be automatically predicted when products change. The lack of such intelligent modelling techniques has serious financial consequences on manufacturing systems. For example, the majority of automotive and aircraft manufacturing industries have reported that the inability to predict the effect of changes in the systems have significant negative effects on their profit margins (Shen et al., 2003).

According to Francalanza et al. (2014), semantic modelling can improve data classification and management to enhance product design knowledge. Ontologies have the potential to provide a standardised, formatted and structured knowledge description, which is suitable for manufacturing systems prediction as well as sharable and reusable to systems (Hernández-González et al., 2014). Some other authors (Cai et al., 2009, Alferes et al., 2000, Qi et al., 2001) have pointed out that the application of semantic modelling techniques is still required to solve the following problems:

(1) A common model for manufacturing data analysis and ontology mapping

(2) Product, process and resource components integration is missing

(3) Automatic ontology generation for automation system integration

1.3 Research Problems

There are still some gaps between knowledge representations and reconfigurable manufacturing tools to enable the reuse of existing semantic and ontological data. The first research problem is how can a reconfigurable manufacturing system integrate product, process and resource knowledge to decrease the required skills and design time to launch new products? Another research problem is can product design data be transferred from various domain-specific software to a collaborative and intelligent platform to capture and reuse design knowledge?

Firstly, the current intelligent digital modelling tools are complex and inconvenient for designers to use. This mainly depends on users' experience of product, process and resource knowledge, and such tools currently provide limited intelligence to support cross-disciplinary knowledge. Furthermore, a qualified product designer would still need to understand processes design, (re)manufacturing and reuse technologies in order to make rapid design decisions (Zhang et al., 2012). Thus, reconfigurable manufacturing system requests extraordinary experience of product, process and resource knowledge to develop current manufacturing line. The design time of new products highly depends on the flexibility of reconfigurable manufacturing system.

Secondly, the cross-couple implications of any given product, process or resource changes cannot currently be readily linked together. This is because the meaning of each change and related implication are not easily apparent. Product design parameters are hidden behand software outputs. Rather than excel sheet, software outputs are normally encoded and some files are encrypted (Cai et al.). The difficulty of understanding design data is even harder than decoding those files. As a result, product design data needs be transferred to a collaborative platform for reusing data for effective reconfigurable manufacturing system design.

1.4 Research Aims

The aim of this research is to develop a novel semantic-ontology engineering framework (SOEF), which can enable the seamless integration of heterogeneous

product, process, resource, and requirements data. The ultimate objective is the creation of a novel semantic modelling methodology that can change manufacturing systems performance at an early stage of the design cycle.

1.5 Research Objectives

To achieve the above research aim and solve research questions, the following objectives are examined:

(1) To review current methods utilised by production tools for discovering product, processes and resource relationships.

(2) To classify ontology technologies for reconfigurable manufacturing systems and how semantic modelling methods are applied to product, process, resource and requirement ontologies.

(3) To develop integrated product, process, resource and requirement ontologies using semantic methods that can capture and reuse product design data for processor resource changes;

(4) To present case studies of the modelling methodology with a representative product and evaluate PPRR ontologies with a semantic model.

1.6 Structure of the Thesis

This thesis consists of nine chapters. Chapter 1 is the introduction of this research which describes the background of the research, giving an overview of manufacturing lifecycle engineering and the role of reconfigurable manufacturing systems in this context and how it has been accepted by both academic and industrial experts. It also includes the aims and objectives of the research as well as the research problems to be solved.

- CHAPTER 2 A Review of Existing Ontology Technology for Automation Systems – The beginning of the chapter provides a literature review of interpreted data and knowledge representation. Ontology as a popular knowledge representation methodology is reviewed from the definition and classification perspectives. For automation systems, available ontology technology is reviewed for product design and process planning. The chapter also concludes with a review of ontology implementation, model-driven

design methods, and relevant manufacturing design tools. The last section of the chapter includes an analysis of two example data transformation tools to evaluate the feasibility of manufacturing data representation.

- CHAPTER 3 A Review of Semantic Technology for Reconfigurable Manufacturing System – Based on the shortcomings of current data transformation tools, data integration methods for reconfigurable manufacturing system are initially reviewed. To address ontology auto-generation, semantic technology is introduced for automatic data representation. To address the decision-making requirement in Product Lifecycle Management (PLM), data prediction models are also reviewed. The chapter summarises the gaps between reconfigurable system requirements and current manufacturing systems.

- CHAPTER 4 A Semantic-Ontology Methodology – According to the gaps concluded from chapters two and three, an ontology-based semantic model is demonstrated and a novel PPRR ontology is introduced to support data transformation. The chapter also presents how semantic technology would support data integration and automatic ontology generation for automation systems.

- CHAPTER 5 Implementation of Semantic-Ontology Engineering Framework – To evaluate the PPRR ontology created in chapter four, a Festo Didactic Test Rig was used in the first case study to define the basic manufacturing concepts and verify the modelling of ontology integration. A detailed ontology design is presented for each PPRR ontology. The chapter concludes with an implementation of the semantic analysis method.

- CHAPTER 6 Research Cases Studies – Two case studies of automatic assembly systems demonstrate how the semantic technology would enable the auto data transformation from a manufacturing data format to a knowledge-based ontology structure. For the decision-making process, a rule-based prediction model is evaluated in a virtual manufacturing tool. Based on the capability of Programmable Logic Controller (PLC) code auto-generation, existing process simulation tools would reflect real physical

machine logic. Hence, the results for all case studies are shown in a virtual manufacturing tool.

- CHAPTER 7 Conclusion and Further Work – This chapter concludes the whole research findings and outcomes. According to the identified shortcomings of current automation system, a novel methodology is presented. However, there are still some research works need to be solved in the future research project. The last section summarised the research contributions and consequences, which can be reused to solve future research problems.

CHAPTER 2 **A Review of Existing Ontology Technology for Automation Systems**

2.1 **Introduction**

In this chapter, previous research achievements and deficiencies will be discussed. The state of the art in product design methods and tools will be reviewed determine the product design limitations of information sharing, and the current knowledge-based solutions for manufacturing design systems. The main content includes manufacturing design methods and tools, knowledge-based system design, integrated manufacturing systems, data analysis. At the end of this chapter, a detailed analysis of the gaps will be summarised.

2.2 **Interpreted Data and Knowledge Representation**

Data can only be valuable after being analysed and interpreted with existing knowledge, and information is a bridge between data and knowledge. Knowledge representation has to be completed by processing data and generating further information. To improve the interoperability of data and knowledge, it is essential to have a clear definition of data, information and knowledge to clarify the differences and relationship between them. From the ordinary users' perspective, information, data and knowledge seem to be interoperable and have no difference. Although many authors attempted to give their definition (Hilbert, 2016, Munir and Anjum, 2017, Braganza, 2004), it is still hard to define a common and clear border between what the meanings of these terms and how they are interconnected.

2.2.1 The Concepts of Data, Information and Knowledge

In general, data, information and knowledge are treated as a sequential structure. Knowledge is generated by information and information is extracted from data which is the raw material of digital content. These concepts are the basis of a Data-Information-Knowledge (DIK) model.

A data element is the basic individual item, which can be identified as a set or collection of facts (Zins, 2007b). Raw data has been obtained from observation and has not been processed. It can also be collected, quantified, qualified and stored, but data cannot always be used to solve problems. Data is intended for addressing the issues (Karafili et al., 2018).

Information is processed data in a certain format, which has specific meanings to the users (Davis and Olson, 1984). However, the meaning has different values to the recipients. The contents of text, website and databases are information for computer systems; the intended meanings of definition, sentence and paragraph by author/speaker are information for human cognitive system (Hjørland and Albrechtsen, 1995). Information is also data received by a communication process and provided the value for decision making. As the output of data processing, information has the ability to gain new knowledge and enhancing the existing knowledge (Kebede, 2010).

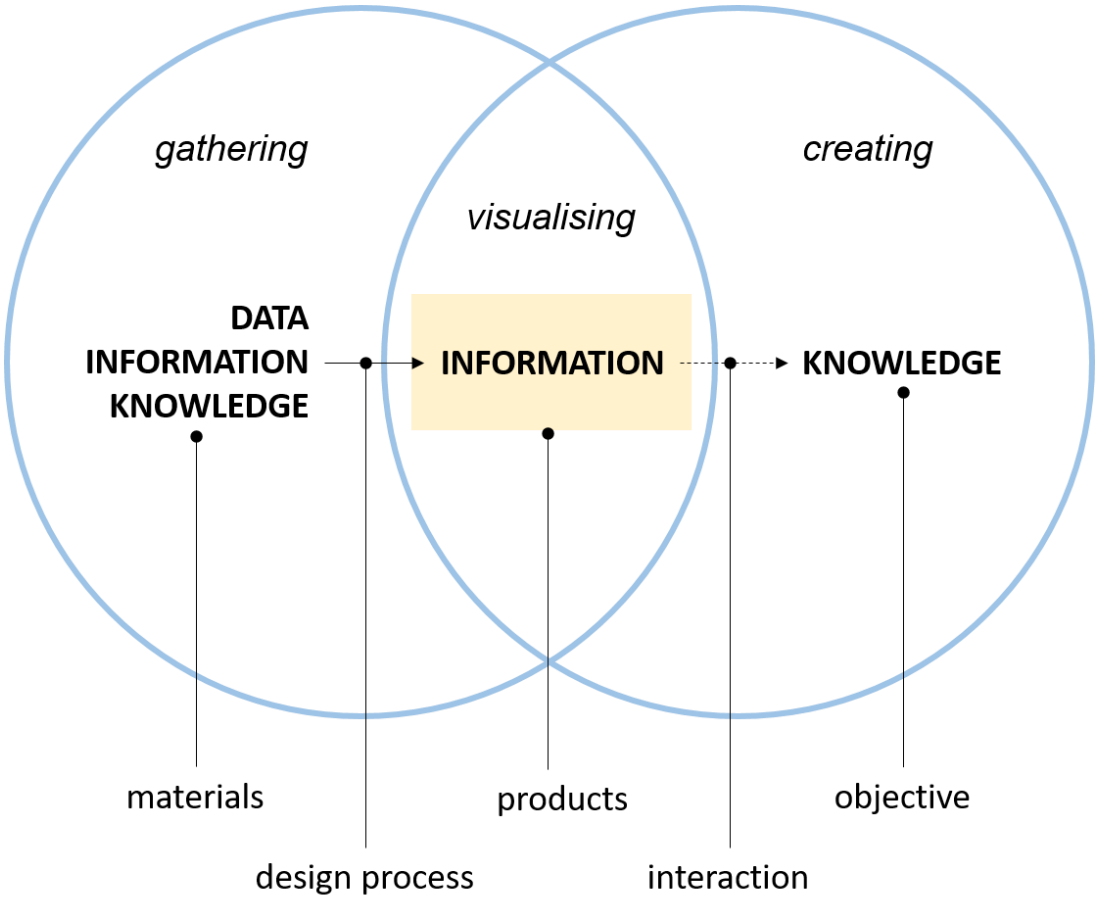


Figure 2-1 DIK Model - Knowledge Representation and Sharing (BuitroN et al.)

Knowledge is appropriate information that has structure and is organised by the recipient (Zins, 2007a). Knowledge is usually described as a concept understood by someone, but others should not know. Thus, the general understanding and belief are knowledge generated from previous experience, contexts and accumulated information. Represented knowledge has also been defined as information visualisation. Knowledge can be learned as another person's information and found outside of the person who contains the knowledge (Liew, 2013). As knowledge is generated by the existing data and information, it can recreate from related data and information.

Based on the definitions above, a DIK model (Figure 2-1) starts with all materials, including Data, Information and Knowledge. Under design processes, collected materials visualised useful information to improve data

representation for a certain scenario. Thus information is summarised of data, other information or existing knowledge. Information regressive transition is a condition to create new knowledge (BuitroN et al.). Thus, knowledge flow can transfer and generate knowledge when information passes from one domain to another. Based on DIK model, human data processes can be represented to Human Information Processing (HIP) model.

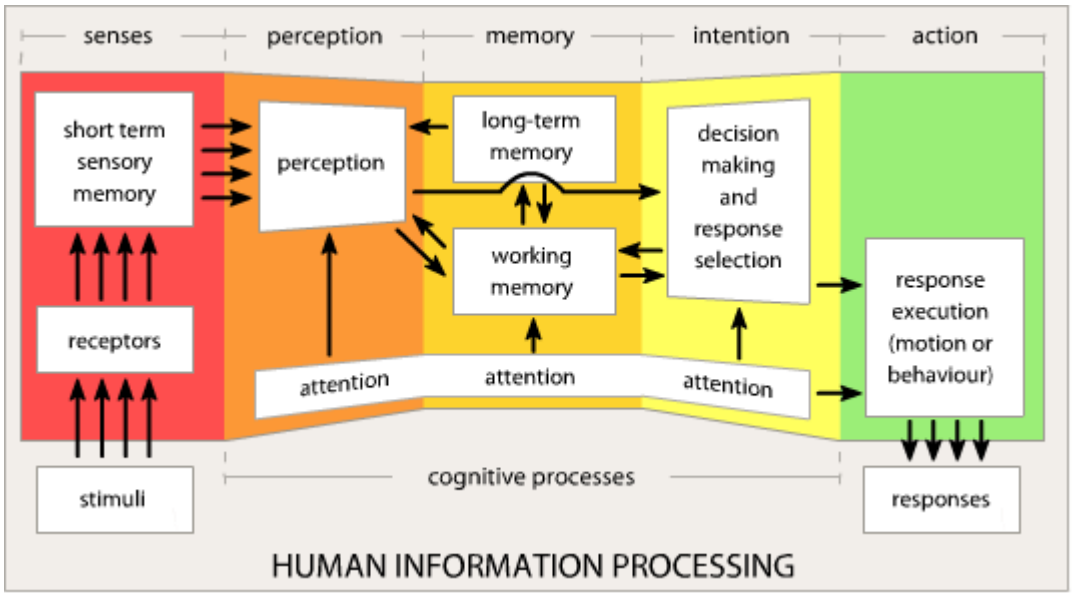


Figure 2-2 Human Information Process from Senses to Action (White et al., 2018)

In this thesis, the HIP is a suitable model of knowledge representation and sharing, because HIP has the same learning cycle as machine learning, such as new object receive, memory retrieval, new knowledge achieve, decision making, and knowledge representation (White et al., 2018). The cognitive processes can be divided into three sections including perception, memory and intention. According to the observation of an object, short memory (working memory) will then be generated and transformed into long-term memory (abstract of knowledge). The intention decides which action or decision will be made. The HIP process flow is demonstrating in Figure 2-2.

2.3 **Ontology Definition and Types**

2.3.1 Ontology Definition

Ontology provides a common language to describe the concepts in different domains and focuses on the relationship among those concepts to assist in the information sharing and knowledge translation (Giovannini et al., 2012). It is typically defined as a set of terms and categories, which means certain specific attributes and relationships in a particular field or domain (Guarino et al., 2009). Ontology structure contains classes, subclasses, relations, property and instance for each class. Ontology is similar to a relational database, but the ontology relationship is different from the relationship in a relational database (Franco-Contreras and Coatrieux, 2015). Firstly, ontologies provide an unambiguous description of the data. The explicit characteristics are manifested in the uniqueness and constraint of concepts' definition, which should not be mixed with other subjective understanding. Those concepts are defined and regulated by academic and industrial specifications, and these definitions will then become a common consensus. Secondly, the ontology should be readable by both computer and human. The formatted structure is required to identify the classification and meaning of ontologies for human-computer interaction. Thus, standardisation feature is another significant difference between ontology and relational databases. Thirdly, ontology should not be confined in a particular scenario and should be reused and updated adapting to wider contexts. The meaning of ontology is related to knowledge capturing and sharing. A strictly regulated concept is not reusable and not extendable, which cannot be included in a rigorous ontology. In summary, ontology contains logical statements for each class that can apply restrictions and rules in the related instance. In database definitions, data cannot assign meanings and logical forms before software analysis. However, ontology axioms are created at the data level, such as what-if statements to describe data logic.

2.3.2 Ontology Types

According to purpose, scope, depth of ontologies, some species are defined and distinguished in many of the literature. There are typically three levels of ontology: Generality (Dobson et al., 2007), Formality (Usman et al., 2013) and Applicability (Mizoguchi et al., 1995) in Table 2-1.

Table 2-1 Ontology Classifications

Level of ontologies	Classification	Difference	Source
Generality	Foundational	Domain-independent	(Dobson et al., 2007, Khan and Luo, 2002)
	Core	Domain-dependent	
	Domain	For a particular domain	
Formality	Lightweight	Simple taxonomies	(Gómez-Pérez et al., 2006, Bukhari and Kim, 2012)
	Heavyweight	Semantic concepts and relationship	
	Informal	Vocabulary and hierarchical relationship	(Rani et al., 2017)
	Formal	OWL format	
	Semi-formal	Represent concepts, objects, predicates	
Applicability	Content	Knowledge sharing	(Mizoguchi et al., 1995)
	Communication	Black box test	
	Indexing	Associating indices	
	Meta	Retrieval information	

2.3.2.1 Generality Level Ontologies

At the general levels of the foundation, ontologies can be divided into Foundational, Core and Domain Ontologies (Ruy et al., 2017). The

Foundational Ontologies are the highest performance at the general level and all the ontologies are the most basic models and general concepts, which contain the relationship between objects in different areas including dependency, classification and events. Domain Ontologies describe all the concepts in a particular field, such as the prototype of manufacturing life cycle simulation (Rani et al., 2017). Core Ontologies mainly define the relationship between the foundational and domain ontologies that provides structured knowledge to a specific domain and relationship between different areas in this domain such as business, application, and communication. In addition, core ontologies enrich the domain ontologies and also enhance foundational ontologies by building up detailed concepts and relations between each domain ontology.

2.3.2.2 Formality Level Ontologies

Based on specification and capacity, ontologies can be defined as two different categories: lightweight and heavyweight ontologies. Lightweight ontology normally describes simple definitions, concepts, and basic relationships, while heavyweight ontology not only contains a lightweight ontology but also provides the classification of concepts, axioms and specific individuals.

According to the complexity of each ontology, lightweight ontology is the first step of creating a complex ontology and also it is the basis of heavyweight ontology. However, lightweight ontology cannot describe the meaning and attributes of concepts in the domain ontology. In comparison with lightweight ontology, heavyweight ontology is complicated and not easy to generate. However, the constraint characteristic provides a good opportunity for integrating ontologies across different domains.

Rani et al. (2017) mentioned there is a new way of classifying ontology by formality level including informal ontology, formal ontology and semi-formal ontology. Informal ontology only defines the vocabulary of concepts and the hierarchical relationship with the taxonomies, such as website indexing ontology and knowledge retrieval ontologies. Formal ontology is defined as

the language by using OWL format, such as OWL 1 (12 November 2009) and OWL 2 (11 December 2012) Web Ontology Language. Semi-formal ontology is a structure ontology format between formal and informal ontologies. The most famous semi-formal ontology language is RDFS, which is a semantic ontology instance. RDFS can be retrieved, reused and integrated to extend the domain ontology and then apply ontologies in the actual projects.

2.3.2.3 Applicability Level Ontologies

According to Mizoguchi's classification (Mizoguchi et al., 1995), ontologies can be classified into four categories (content ontology, communication ontology, index ontology and Meta ontology) by knowledge of the application, used time and environments. The content ontology is the main ontology type for knowledge sharing and reuse, which contains content vocabulary, concepts and knowledge information. Between each content ontology, communication ontologies are used to test ontology or pass ontology via a black-box test, without useless or sensitive information. In order to improve query efficiency, index ontology was designed as the associating indices to establish a quick index system between different ontology objects. Most importantly, Meta ontology provides a distributed query retrieval environment to create, edit, modify and query using ontologies.

2.4 Ontology Technology for Automation Systems

One production line designed to optimise for one or two series of products, but cannot be effectively evaluated when product or production process changes. For this reason, robots and automation systems need to support the storing and sharing knowledge to extend current process capability for the next generation. To develop an extendable and robust automation system, it is important for researchers to fully understand the implications of other objects and knowledge, such as product, process, and resource knowledge in other manufacturing systems.

Ontologies have been used by a number of researchers to integrate the product with automation processes and resources. According to Hernández-González, et al. (Hernández-González et al., 2014), the ontology provides a

standardised, formatted and structured knowledge description, with the benefit of being shareable and reusable. In general, ontology is useful as a key technology to extract and integrate manufacturing systems with design data from design software and database (Ferrer et al., 2015a). By following the ontology rules, knowledge-based systems can be established to support the retrieval of product design concepts. However, retrieval cannot fulfil all the requirements of the manufacturing design system. For example, current product designers do not get real-time reports about available resources during the design phase. Data search methods are still based on text retrieval rather than text association. Another reason is that component naming rule is not unique to all engineers and projects. Hence, normal retrieval methods are not an effective way for advance manufacturing systems.

2.4.1 Ontology Development

A digital and intelligent production line requires automated manufacturing processes. Automatic information integration has become increasingly important in the context of Industry 4.0 with informatics technology. Increasing customisation and the demands of product upgrades need to be solved by applying an intelligent manufacturing model. Previous researches have achieved manufacturing software integration or shareable data type generation. For example, computer-aided manufacturing (CAM) software can transfer a computer-aided design (CAD) model to a Computer Numerical Control (CNC) machine, in order to support system integration and reduce mistakes during file transforming. (Suh et al., 1995, Bahr et al., 2001). With the rapid development of information technology, CNC systems combined with “plug and play” smart sensors can provide powerful processing capabilities and real-time data analysis during machine operation (Wang et al., 2004).

Industry 4.0 extends emerging technologies by integrating technologies including the Internet of Things, cyber-physical systems and service innovation for digital factory systems design (Lee et al., 2014, Dombrowski and Wagner, 2014). These research programmes have contributed to the development of the concept of the Digital Factory (DF), a collection of methods, models and tools to provide support for manufacturing design and factory

planning based on manufacturing systems simulations (Stef et al., 2013, Wenzel et al., 2005). Manufacturing design methods and tools are therefore their key drivers in the integration of different levels of industrial processes.

Semantic integration improves the efficiency of data transfer between different systems and supports existing data reuse in terms of data rebuilding. Excellent semantic-based applications are currently being introduced in commercial business systems and will become more widely used in many other areas of industrial design systems, e.g., in assembly sequence planning, e-procurement and information retrieval systems (Efthymiou et al., 2015).

Ontology as a conceptualised logic specification is being extended from Artificial Intelligence to a number of research areas (Pradhan and Varde, 2016). At the same time, ontology is being widely used in the Semantic Web and the World Wide Web. Ontology-based systems are suitable for the rapid updating of the knowledge system, for example, dynamic scheduling, integrating metadata and flexible manufacturing systems (Cheng et al., 2017). This method is also constantly being evaluated in the product design and manufacturing field via the sharing of information and engineering knowledge. Ontology specialises in knowledge management, re-use of knowledge and the ability to handle the complex dependencies among different engineering domains. Ontology-based methods provide an excellent opportunity to share information at the application and system levels. To develop ontology for product design, a couple of product design methods are reviewed in the next section.

2.4.2 Model-Driven Design Methods

A design method is key to a product development process. This is mainly to provide a design selection criterion and enhance the design outputs. Some early researchers in product design focused on Design for Manufacture and Assembly (DFMA), whilst others approached designing from process and enterprise modelling perspectives (Changchien and Lin, 1996, Agyapong-Kodua et al., 2009). For example, the methods of Boothroyd Dewhurst, Lucas and Hitachi are widely applied in industry for product design, evaluation and

modification (Huang and Mak, 1999). There are also established CAD/CAM tools for manufacturing design and other techniques for optimisation, including genetic algorithms, simulated annealing and hybrid colonies. Despite these existing techniques and the tools already in place, design knowledge is still difficult to reuse as it mainly depends on the designer's skills. As a result, the authors represent that knowledge management for manufacturing and assembly will help product designers familiar with manufacturing knowledge. Knowledge of assembly sequences and planning will facilitate the development of enhanced products and limit manufacturing difficulties.

A manufacturing design framework aims to establish a platform by using different analysis and design methods from multiple disciplines as well as design concepts to generate concurrent and coherent solution sets (Tolio et al., 2013). With the help of Concurrent Engineering concepts, manufacturing designers can perform a lot of engineering analysis at an early stage of the design process, because the drive towards integrated knowledge sets can improve the decision-making process (Wagner et al., 2014). To facilitate such decision making, robust technologies with the capability of supporting dynamic integration of different data and knowledge sets are required.

Figure 2-3 shows a flexible factory system design procedure, which emphasises a synchronisation process, is the first step of the factory design method. Step 1 includes product design, processing planning and investment planning (Francalanza et al., 2014). Additionally, step 1 feeds into the next step, which is demand analysis and then synthesis. The figure shows that simulation of the manufacturing system is required before evaluation. Despite the design procedure, the present authors also point out that there are two clear shortcomings. Firstly, it does not include resource planning that will indeed affect the decision-making process. Secondly, in order to shorten the digital lifecycle and reduce unnecessary costs, demand analysis should precede the product design process. Another observation is that a digital factory must be supported by the key computing and technical infrastructure, e.g. for real-time data manipulation, 3D visualisation and interoperability (Shariatzadeh et al., 2012).

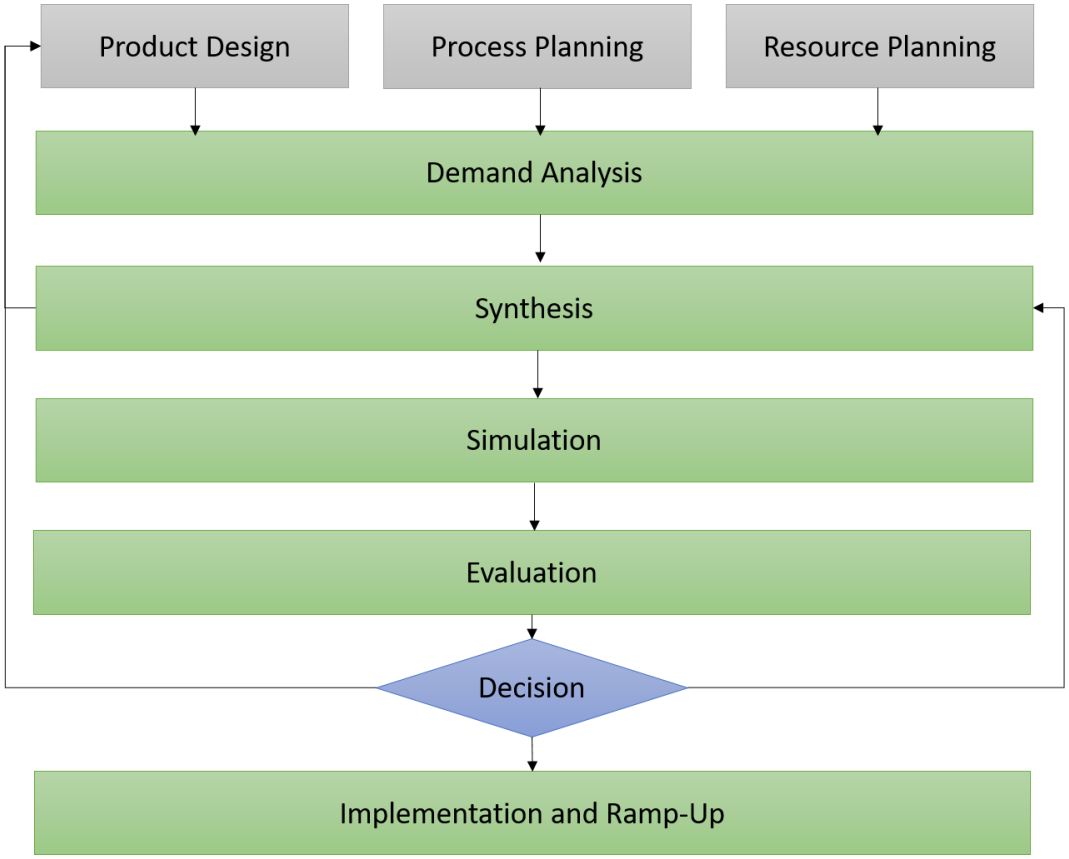


Figure 2-3 A Modifiable Factory System Design Procedure (Francalanza et al., 2014)

Traditionally, design methods are generally composed of continuous design flow processes. One of the most widely understood methods is mentioned by Pahl et al. (2007). Their methodology classifies design into four main phases: product planning and task definition, conceptual design, embodiment design and detail design (Wu et al., 2015, Dieter et al., 2009). Typically, the process logical sequence is a top-down design methodology, which starts from the problem definition to the detailed design. After reviewing the literature (Pahl et al., 2007, Hapuwatte and Jawahir, 2019), it shows the steps of describing the common stages in most design projects (shown in Figure 2-4).

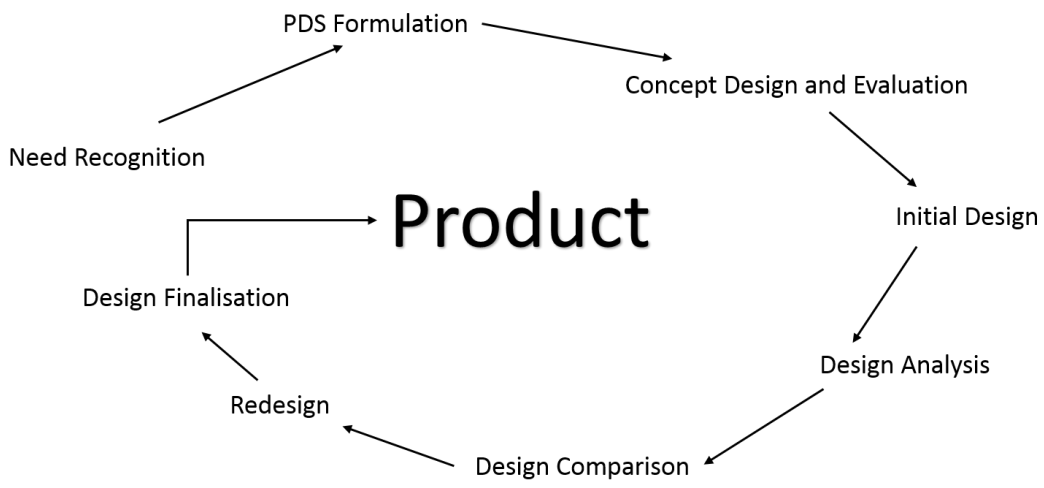


Figure 2-4 Common Design Stages (Pahl et al., 2007, Hapuwatte and Jawahir, 2019)

Design for X (DFX) is an embodiment of several design methods. The methods are Design for Manufacture (DFM), Design for Assembly (DFA), Design for Quality (DFQ), Design for Disassembly and Recyclability (DFDR), Design for Environment (DFE), Design for Maintainability (DFMT) (Agyapong-Kodua et al., 2013). Table 2-2 presents the indications of strengths and weaknesses of five of the major design methodologies that have been mentioned in the previous sections. Yassine and Braha (2003) have given an overview of the concurrent engineering concept that was initially presented by Institute for Defence Analyses (IDA) in 1988, and which has been adopted by many organisations including Siemens.

During product design, concurrent engineering will integrate all the processes by using a collaborative working model, which can assign different jobs at the same time to compress the product lifecycle. However, this approach requires process designers to have excellent coordination skill and great process design experience. Normally, the process designers need to be familiar with all details of process arrangement during the whole producing process (Sethi et al., 2001). Additionally, concurrent engineering also requires a clear understanding of customer requirements, such as product quality, cost and process schedule. (Agyapong-Kodua et al., 2014d).

Table 2-2 Review of Some Existing Design Methods

Design methods	Strengths	Weaknesses
DFM	Flexible cost analysis and minimum cost estimation to reduce process cycle time with CAD/CAM support (Kuo et al., 2001)	Limited manufacturing assembly solution for certain circumstances to control assembly cost (Lozano et al., 2016)
DFA	General methodologies for most assembly processes including generating sequences, predicting assembly times and associated costs based on the CAD system (Holt and Barnes, 2010)	Some solutions cannot be achieved through real production system of specific organisation (Cermak et al., 2011) Does not simulate assembly system environment at different work loading conditions and cannot be integrated with the virtual process and resource modelling system (Boothroyd and Alting, 1992)
DFQ	Excellent quality control system and focus on user experience, product quality and sustainable development of product (Lentsch and Weingart, 2011)	Lack of correlation to control product quality and production process. Ignore the assembly system design (Li et al., 2008)
DFDR	Flexible product design to support the re-manufacturing and recycling Disassembly sequences management to reduce maintenance time and aim to reduce life cycle cost (Ramirez, 2007)	Excessive recycling will lead to increased costs Processing technology and manufacturing technology will affect disassembly results and cannot simulate virtual models for assessing disassembly using hypothetical shop floor space parameters (Gupta and Lambert, 2016)
DFMt	Promote low-cost products Consider the maintenance measures and trying to reduce maintenance, assembly and disassembly costs (Kuo et al., 2001)	Misses product adaptability due to singleness of design method Limited product cost factors (van Houten and Kimura, 2000) Needs designers who know specialised knowledge to design the maintenance sequence maintenance (Liu and RA Issa, 2014)

Based on the review of design methods, computer-based support is used in many DFX methods. In the next section, manufacturing design tools are evaluated for data structure development.

2.4.3 Manufacturing Design Tools

Currently, there are some useful modelling tools for integrating production capability, hardware systems and computer control systems (Agyapong-Kodua et al., 2014c). CAD, CAPP and CAM can be used to process and integrate information through the functional design to process planning stages.

CAD defines a geometric product model, whilst CAPP provides options for process planning (Xu and He, 2004). Traditional design tools help to reduce the complexity of paper mapping and manual modifications. Examples of such tools are ProEngineer, SolidWorks and CATIA. However, current design tools have limited reusability and dynamic integration capabilities, because product models cannot be reused for another product and CAD models cannot automatically link to process and resource design tools.

Culler and Burd (2007) have also applied CAPP for cost analysis. Their technique provides feedback to designers to help avoid any unnecessary costs. CAM would focus on how components of products can be realised. There are some advantages of applying CIM, including reduced demand for direct labour, lower overall manufacturing lead and cycle time, improved technological levels and high flexibility (İç, 2012). However, traditional CIM applications lack the support of knowledge-based systems to enable previous methods and models to be effectively reused. To resolve this problem, many enterprise modelling and related techniques have emerged to help the reuse of manufacturing knowledge. For example, the GRAL modelling approach uses effective decision structure to describe and design business processes for manufacturing design, but it cannot effectively identify the decision domains, processes and resources involved (McCarthy and Menicou, 2002). In addition, an integration system including Model Driven Architecture (MDA), Model-Driven Interoperability (MDI) and ontology development methods have been applied to enhance rapid system reconfiguration and interoperability.

However, semantic-based MDI system has not completely solved the problem of inter-systems complexities along product lifecycle (Chungoora et al., 2013).

2.4.4 Process Selection and Assessment

To integrate design, process and reconfiguration data, a couple of digital modelling tools have been developed, such as vueOne (Alkan and Harrison, 2019), Visual Component, CATIA. These tools support product design and process visualisation to verify assembly process before physical development (Jbair et al., 2019). However, process selection and optimisation are still challenging current manufacturing systems. To avoid the misunderstanding of requirements, designers define detailed requirements for product, process and resource at the early product development stage (Ramis Ferrer et al., 2016). Nevertheless, their integration is currently not intelligent, as product requirement changes cannot be adequately reflected in process and resource requirements. This means the process and resource requirements do not link to product requirements during product design (Chen et al., 2014).

Process performance is generally used to define and evaluate a system in order to improve productivity, portability and scalability of the product design process at the system level (Xiong et al., 2010). In the manufacturing area, Discrete Event Simulation (DES) has been able to simulate a virtual production process based on cycle time, cost, failure rates, and idle time (Arinez et al., 2010). Different indicators are assessed by methods including qualitative and quantitative analysis. For example, credit-based ranking, scaled scoring, benchmarking comparative method, EIAR flowcharting, and subjective marking (Ugwu and Haupt, 2007). However, such design tools cannot be used to predict possible process changes at the early product design stages. Ontology has been developed to connect process and product design for manufacturing tools.

2.5 **Ontology Development Methodologies**

To create a manufacturing ontology, some methodologies have been launched to support ontological model development over the last two decades. In 1994, the U.S. Air Force defined an ontology method as structure semantic

information modelling called IDEF5 (Lim et al., 2011, Yu et al., 2011). An ontology acquisition process was developed based on five steps (Benjamin et al., 1994):

1.**Organising and Scoping of the Project**: the structure and content of the project are described in this part and the main objectives of ontology development are clearly specified.

2.**Data Collection**: The definition of raw data is classified for ontology development and the method of obtaining data are summarised from different domains.

3.**Data Analysis**: This part is used to analyse the existing data material to establish an initial ontology for knowledge engineers and domain developers.

4.**Initial Ontology Development**: By developing prototype ontologies, ontology classes, properties, attributes and relationships are refined and given detailed specifications needed for the next step.

5.**Ontology Refinement and Validation**: This phase integrates the known information with the ontology. Through a refinement procedure, ontologies are summarised in specification form to be evaluated by domain experts.

Based on the IDEF5 methodology, Uschold and Gruninger (1996) added another documentation stage to standardise the ontologies and support a foundation for future ontology development. METHODOLOGY introduced iterative ontology development and focused on maintenance aspects (Fernández-López et al., 1997). Reused knowledge and existing ontologies are referenced in Noy and McGuinness' methodology to improve the usability of the ontology (McGuinness and Van Harmelen, 2004). They report that, through an in-depth knowledge structure analysis, ontology population should transfer from manual to automated population in the future.

2.6 Transformation Tools

Despite the advantages of ontology technology, the traditional industry data are still stored in Structured Query Language (SQL) or NoSQL database,

which is difficult to represent at the ontology (Tan et al., 2017). Hence, some transformation tools have been developed to allow the combined benefits of the respective approaches to be exploited. Transformation tools will enable the sharing and reuse of knowledge structures to support the existing data sets' integration and analysis. So the use of relational databases-based conversion tools has become an ideal method of improving ontology development efficiency, e.g., such tools as DB2OWL, RDB2Onto, and OWL2DB. Also, they can address the time-consuming ontology development process that is faced by knowledge engineers (del Mar Roldan-Garcia et al., 2008). The data transformation model can convert RDF data to Relational Database (RDB), XML file and JSON file formats (see Figure 2-5).

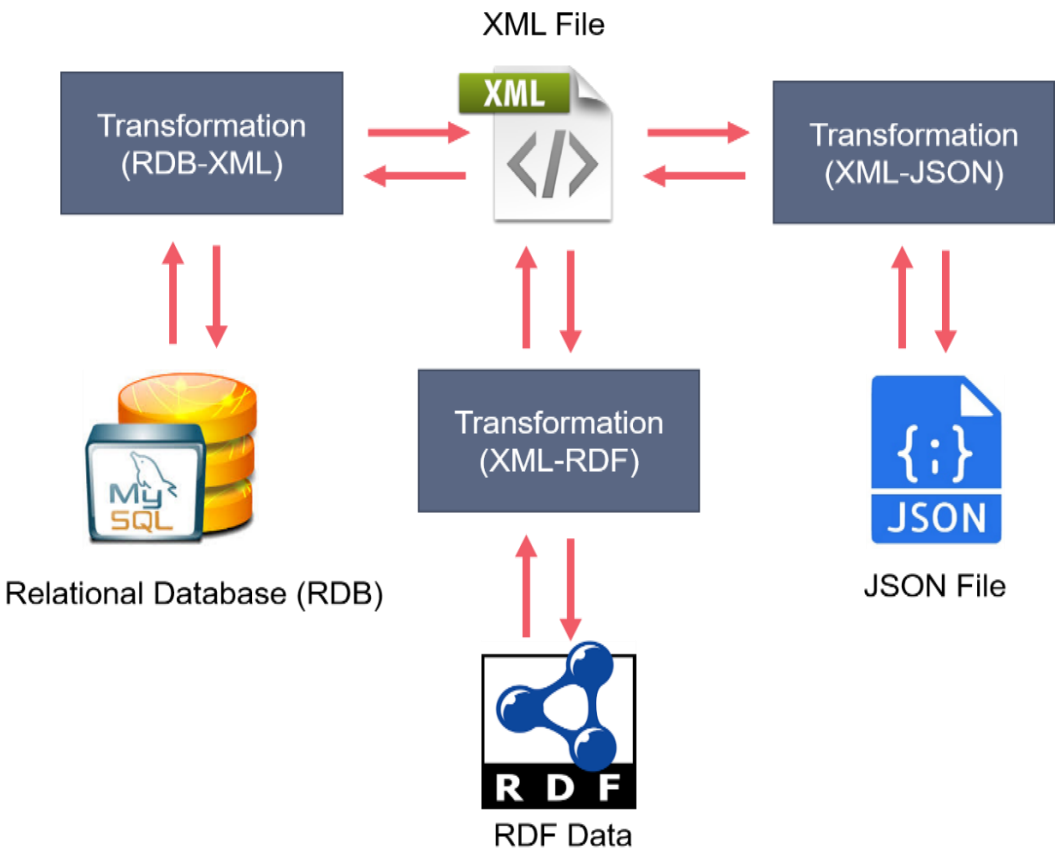


Figure 2-5 Data Transformation Model (Malik et al., 2018)

2.6.1 DB2OWL

DB2OWL is a conversion tool that can automatically generate ontologies from relational databases via mapping database tables and description logic by

using OWL-DL language (Altowayan and Tao, 2015). Based on these algorithms, data are translated into equivalent ontology components. For example, tables are represented as classes in ontology description; columns and rows are represented by properties and instances; the relations in database schema are the relationships among ontologies domains. The advantage of this and similar tools is automatically generating records for logging ontology mapping processes, which includes (1) each corresponding description for ontology components, (2) conceptual relationships between ontologies and databases, and (3) mapping history of instances and attributes (Jayakumar and Shobana, 2014). However, this tool is database specific and only supports Oracle and MySQL due to meta-data limitations. Additionally, data mapping cannot span across different databases to generate ontology.

2.6.2 RDB2Onto

The automatic generation of ontologies is usually focused on mapping relational databases with ontology concepts, such as DB2OWL, D2R and R2O (Barrasa Rodríguez et al., 2004). RDB2Onto is a SQL query-based RDF/OWL translation tool that can be used to transfer existing data to ontology templates by using only SQL queries (Octaviani et al., 2015). Figure 2-6 describes the data flow and Ontology mapping processes in RDB2Onto.

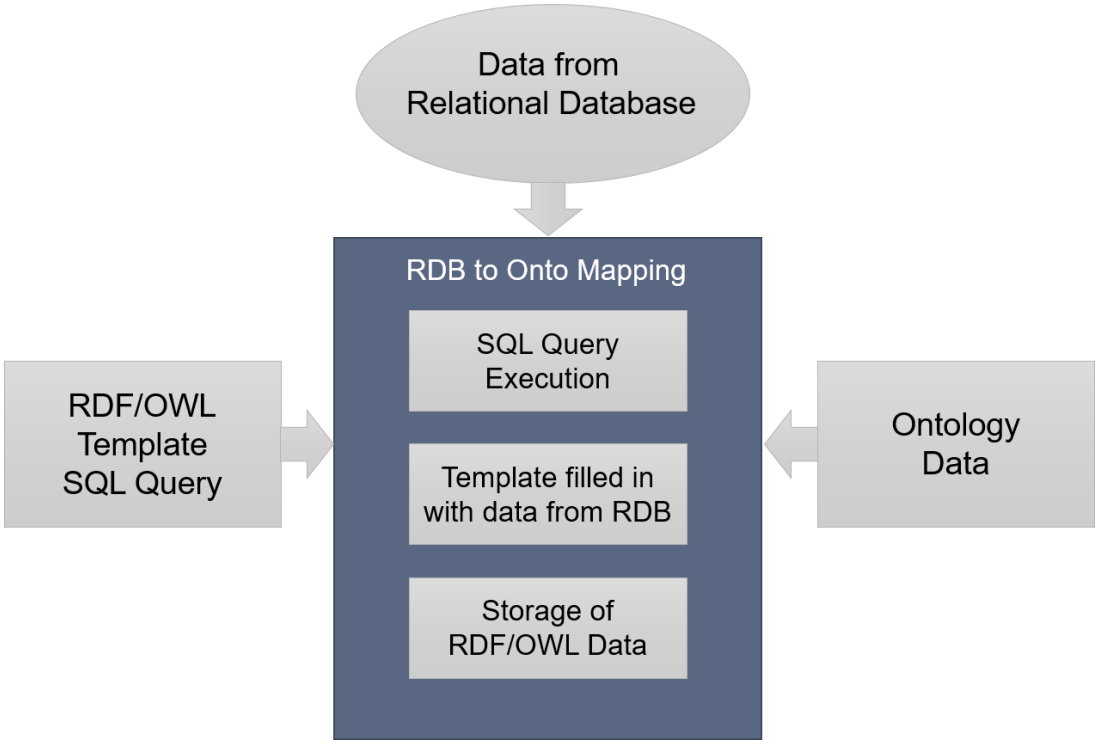


Figure 2-6 RDB2Onto Architecture

To analyse XML schema in ontology template, data will be merged into an ontology data format. This tool is developed in JAVA using Sesame and Jena libraries, which support SPARQL to connect ontology with a MySQL database. Moreover, it can also be used for other relational databases. The advantage of this solution resides in its simple and easy operation through a graphical user interface (Laclavık, 2007). RDB2Onto also provides an excellent opportunity to customise instances and create decision-making rules by using an ontology library. Unlike DB2OWL, this approach cannot directly generate database instances to ontology. Furthermore, the main components of this tool are the OWL Builder and the OWL Writer, which cannot preserve ontology structural constraints. Thus, this tool does not support reasoning tasks of extending ontology with rule predication.

2.6.3 Others

There are other solutions that permit the transformation from OWL to relational database form (Ho et al., 2015). In fact, this work describes the main principles for mapping OWL elements to relational database schemas within a specific

tool, and it' is based on the OWL2DB transformation algorithm (see Figure 2-7).

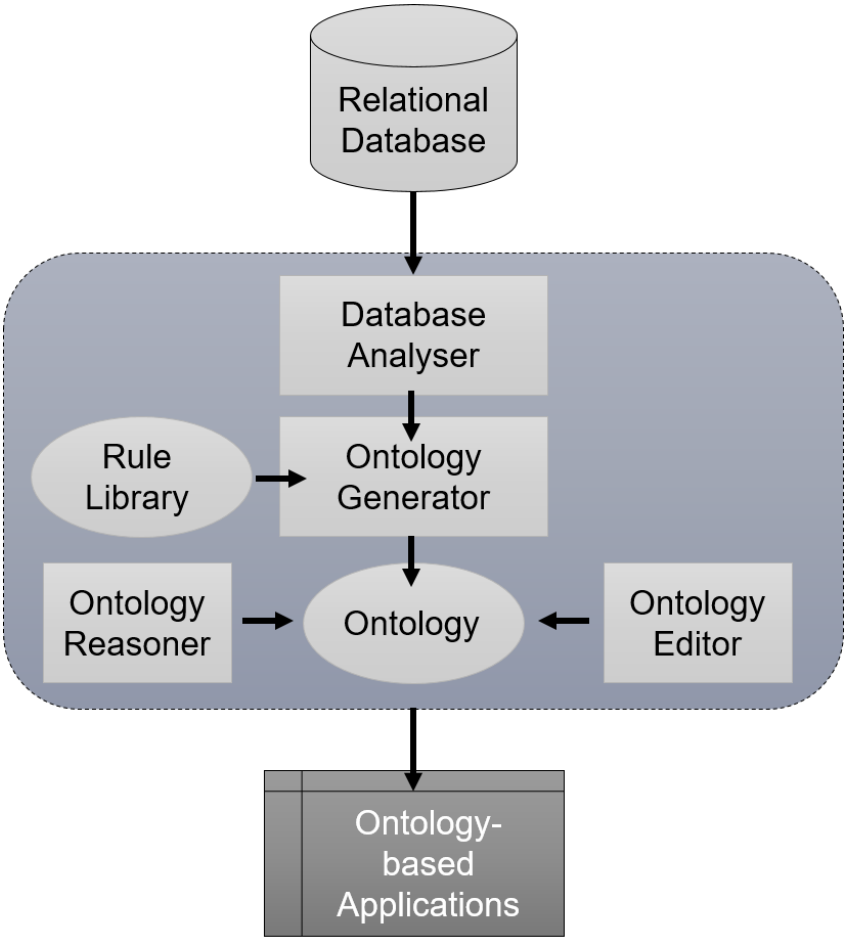


Figure 2-7 Ontology Transformation Framework

Furthermore, a qualitative comparison between similar transformation solutions is provided by this author and the aforementioned article demonstrates that the mapping between ontology and database models is feasible and it must be taken into account in environments that employ both types of modelling approaches. However, OWL2DB focuses on a one-to-one class relationship and a breadth-first search method. As a result, this tool's performance is limited by the transformation algorithm. Depending on the specific case, this tool may not be able to create all relationships between tables or classes. Moreover, the knowledge can only be transformed to OWL Lite syntax and part of OWL DL syntax.

2.7 **Summary**

Ontology was defined as a set of terminologies and provides specific meanings and relationships in particular domain areas. Ontologies can be classified into three-level ontologies including generality level, formality level, and applicability level from different perspectives. Based on the capability of the individual ontology, suitable ontology development methodologies need to be applied to combine different types of ontologies. However, current automation systems do not have a clear specification to develop and implement ontology technology for manufacturing tools. The manufacturing design methods are reviewed to establish an automatic product-process-resource ontology method. However, these methods cannot integrate product, process, and resource components in the same software. Every component has different formats, presentations, and meaning. To translate all components to the same ontology structure, previous researchers have, to a very limited extent, built transformation tools to convert different data to ontological format. However, data conversion is not just a formatting process, but also a process of semantic integration. In current manufacturing systems, therefore, there is a need for a robust ontology development platform with semantic technology to support automation system design.

CHAPTER 3 **A Review of Semantic Technology for Reconfigurable Manufacturing System**

3.1 Introduction

Ontologies are a key technology to extract and integrate the manufacturing systems design data from design software and their databases. Using ontology, knowledge-based systems can be implemented to capture product information and design knowledge. However, information retrieval only cannot fulfil all the manufacturing system design requirements. For example, the usability of current manufacturing resources is not possible to retrieve in real-time for product engineers. Usability information is usually stored into an isolated system and the availability for each machine is separated as well. It is difficult to integrate all data and send to product engineer in real-time. Throughout a manufacturing program, various engineering ontologies need to be shared and integrated at a semantic level. However, because of the different definitions of ontologies and ontologies structures, the re-use and integration of various ontologies models is extremely difficult.

Jong et al. (2013) used a three-tier architecture, which includes a historic knowledge platform, built-in API and MS-SQL database management systems to support model design. Also, a demand-driven knowledge acquisition system based on the demand pre-processing, knowledge retrieval and searching has been implemented (Chen and Chen, 2014). Generally, the use of ontologies to support Product Lifecycle Management (PLM) would attempt to integrate various product development processes using knowledge from several participants. However, PLM solutions are closed and difficult to integrate with third parties databases. Moreover, the integration of their internal software modules is generally not achieved in a robust and systemic manner, and product design changes cannot be adequately used to drive change requirements for manufacturing process and resource.

Semantic technologies use and process data from different stakeholders, and offers an opportunity to implement an ontology-based semantic system (Hui

et al., 2007) providing a real-time integration of various knowledge domains. Using semantic modelling approach, product information modelling can be developed and applied by manufacturing process planner to obtain the necessary product information and input directly to the product design (Izza, 2009). Despite the fact that there is an increasing number of semantic tools and structural model development, this area is still facing a great challenge in achieving process prediction and the selection of appropriate manufacturing resource as a result of product design changes.

3.2 Integration Methods for Automation System Design

Integrated automation systems design approaches used various different analysis and design methods to provide a coherent engineering platform allowing concurrent engineering processes across multiple disciplines. Manufacturing engineers require design methods that can improve the capabilities of the existing manufacturing systems at the product design and process planning's early stages (Wagner et al., 2014). Typically, traditional manufacturing systems engineering methods are only designed for particular issues and tasks, and usually make use of very specific products and processes models (Tolio et al., 2010). Some integrated manufacturing system frameworks are used for resource sharing, data transfer and to support engineering communication and collaboration. For example, the Virtual Factory Framework (VFF), the Sustainable Factory Semantic Framework (SuFSeF) and The Open Group's Architecture Framework (TOGAF) are three architectures for manufacturing systems integration of Product-Process-Resource (PPR) (Lopez and Blobel, 2009, Terkaj et al., 2014, Horbach, 2013).

3.2.1 Virtual Factory Framework

VFF is a framework that achieves integration of process and resources information into a shareable virtual environment while supporting the whole product lifecycle of manufacturing planning (Efthymiou et al., 2015, Colledani et al., 2013). The key aspect of VFF architecture is a Virtual Factory Data Model (VFDM), which uses semantic technologies to define various types of data and knowledge stored in a shared knowledge repository using a universal

language. Figure 3-1 shows the shared product lifecycle and factory lifecycle. Product lifecycle contains planning, development, design, rapid prototyping design, production, usage, service and recycling. And factory lifecycle includes investments planning, engineering, process planning, construction, ramp-up, production, service, maintenance and dismantling or refurbishment. For digital and virtual design stage, product and factory can be presented within R & D strategy planning technology development and simultaneous engineering. The crossing point for both life cycles is the Production stage.

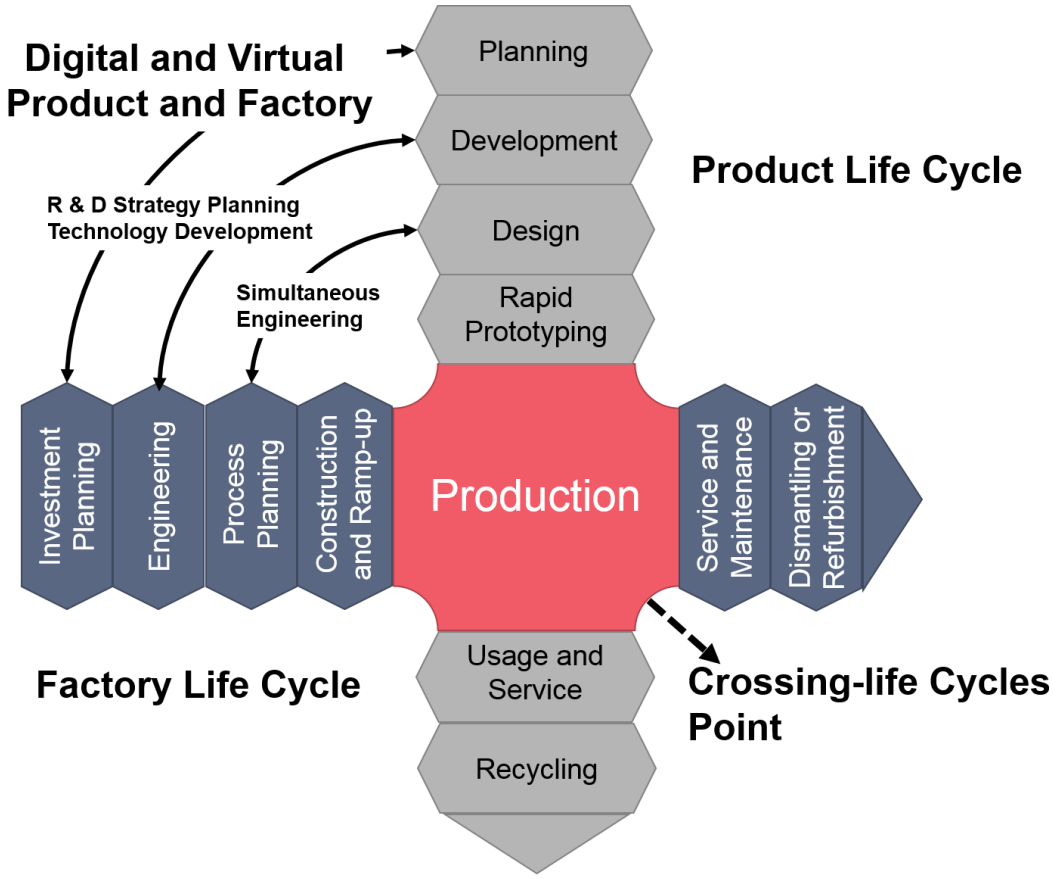


Figure 3-1 Crossing Life Cycle for Virtual Factory Framework (Azevedo et al., 2010)

However, the VFF architecture is a general architecture that does not allow handling low-level relationships which for instance are necessary to automate the definition of detailed process design and control logic required to characterise manufacturing systems' behaviour. Moreover, the many applications required by the framework are integrated via specific connectors, which provide a connection between platforms and support data conversion.

However, typically with such approach to integration, connector design massively affects the integration complexity and the overall system's efficiency, as many simultaneous connections between complex applications and large data management systems often result in system overload and inconsistency.

3.2.2 Sustainable Factory Semantic Framework

In order to integrate a digital modelling tool with an interactive platform, SuFSeF has focused on the development of a specific middleware that supports Input/output data conversion, and transfer from the original database to the shareable data warehouse of the virtual factory platform. Terkaj et al. (2014) mentioned that the SuFSeF suits and expands the VFF platform in order to optimise the architecture of factory design and management solution. An integrated middleware was added to link digital modelling tools and data repository and to support data layer integration. The middleware makes use of ontologies (see Figure 3-2) to achieve software and data management systems' integration.

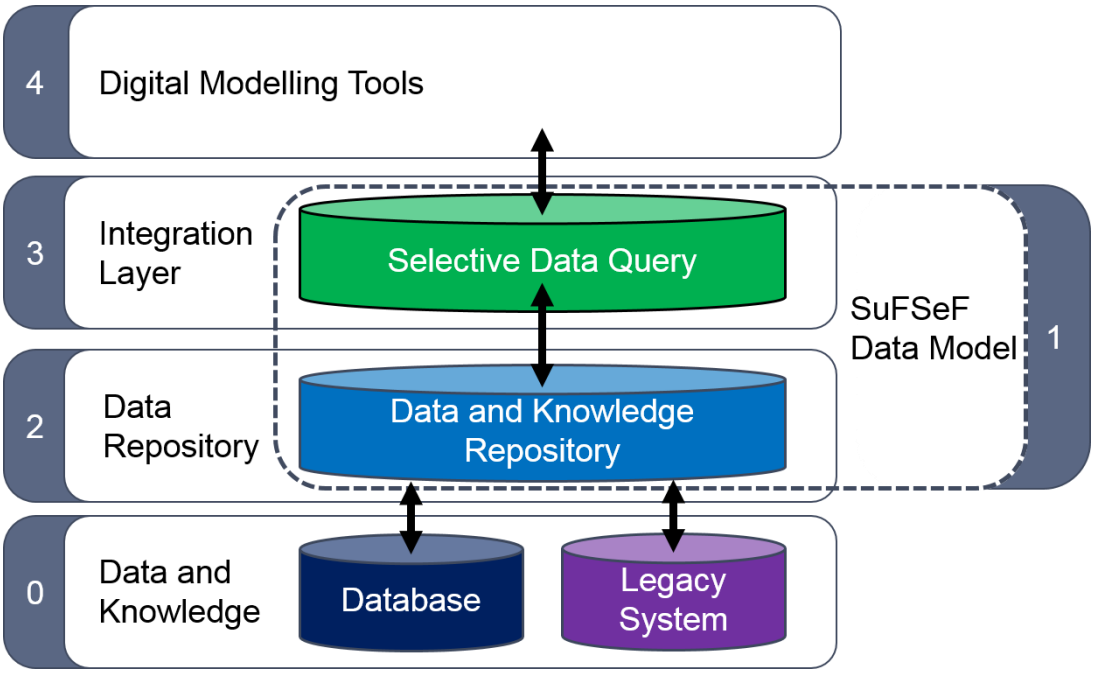


Figure 3-2 SuFSeF Architecture (Tolio et al., 2013)

However, SuFSef architecture does not provide individual Product-Process-Resource (PPR) data models and does not directly support their integration.

After obtaining the access control, the data query is executed at the data presentation layer that will be able to acquire the knowledge-based feedback by using the semantic logic system. Although SuFSeF provides an opportunity to achieve interoperability between various systems within or across organisations, the specification and mechanisms of interoperability, knowledge relationship among the three major sections in manufacturing engineering information and data sets, namely product design knowledge (P), process design knowledge (P), and resource planning knowledge (R) are not explicitly defined. The integration of PPR should be reflected in the data layer such that a series of related product design information can be explored by the semantic query functions, which is not the case.

3.2.3 The Open Group's Architecture Framework

The Open Group's Architecture Framework (TOGAF) is an industry-standard to develop enterprise architecture and the Architecture Development Method (ADM) of TOGAF is to support the design of manufacturing systems (Wahab and Arief, 2015, Lopez and Blobel, 2009). The method consists of four architectural of manufacturing information technology, i.e. design, planning, implementation and management (Bun et al., 2013). Figure 3-3 shows the development of ADM architecture which begins with the preliminary requirements (Dores et al., 2019). At the preliminary stage, observation and research activates are expected for data collection and analysis. After defining basic requirements, organisation vision is clear and the next is to develop business architecture by using an existing business model. Information and technology design is focused on data flow design and innovation system design. Furthermore, opportunities and solutions are the last part of organisation design stage which reviewed current opportunities and evaluated existing solutions before implementation. However, requirements management is always connected with each stage to maintain organisation objects and business model.

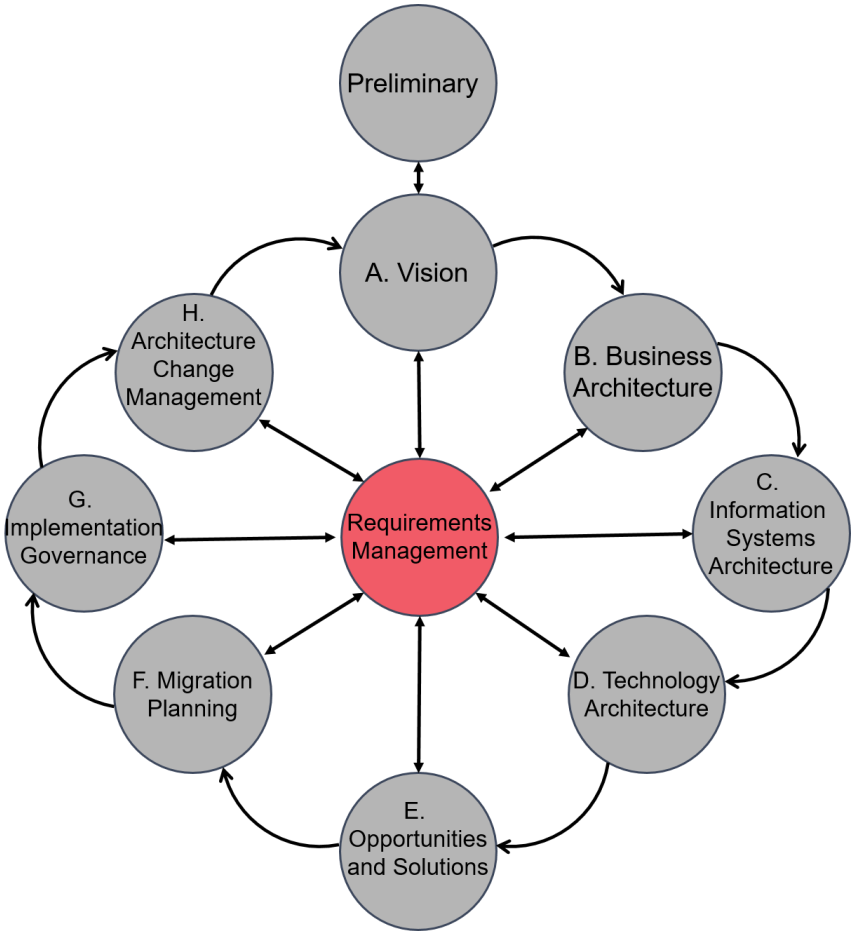


Figure 3-3 The ADM Framework Architecture (Dores et al., 2019)

According to the TOGAF method, the manufacturing systems' design methods and models are the key drivers in the integration of different industrial processes levels. However, concurrent engineering was not considered in the concept of enterprise continuum and also the related semantic technologies were not captured in this framework.

3.3 Semantic Formalism

The engineering of a system (manufacturing system or product) should benefit from knowledge of past engineering and design cycles (da Silva et al., 2014). Most knowledge-based systems rely on shared design databases and ontologies, which formalise the data structures of the PPR data sets and their relationships. Goel et al. (2012) indicated that the use of multimodal reasoning could help support a wide variety of design methods and behavioural models.

Documentation and Annotation is the first step of text mining while human annotation normally is a time-consuming task. Hence, the automatic annotation process is requested to improve text mining effectiveness. However, fully automation process without human interaction is not easy way to implementation. With unfamiliar knowledge, machine cannot recognise it correctly and some time will link a wrong meaning to the content (Altınel and Ganiz, 2018). To able to solve those questions, semantic approaches should provide the following functions or features to improve current documentation annotation issues:

- Documentation annotation should use unsupervised or semi-supervised mining approaches to minimise human effort.
- Annotation library should suit for general scenario and scalable based on existing manufacturing resources.
- After the annotation process, unannotated text should be present to human-readable or recognisable knowledge document.

Several automation systems have been built up with few semantic data analysis tools (López et al., 2012). For example, General Architecture for Text Engineering (GATE) API is a famous development tool of supporting information collected from different data sources and then providing a basic processing resource for information extraction that called ANNIE (A Nearly-New Information Extraction System) (Kim et al., 2015). Moreover, ANNIE contains few natural language processing techniques for information analysis that based on semantic rules, such as gazetteer, NE transducer, POS tagger, English Tokeniser, OrthoMatcher and so on (Fafalios and Papadakos, 2014).

3.4 Automatic Data Representation

The integration of traditional databases has been challenged by complex data structures and the lack of contextual information describing the meaning of the data stored. Ontologies can be used to address data structures and relationships problems. However, data representations are typically identified and integrated by ontology experts, which knowledge and understanding are

limited to a particular engineering domain. As a consequence, many different overlapping and/or inconsistent ontology structures and logics are typically developed within the same organisation, which results in ineffective knowledge representation and systems.

Most of the manufacturing-related ontologies domains have a similar core structure, which defines products, processes, and resources modelling. Core ontologies often have significant semantic shortcomings, such as inconsistent family ontology and parent ontology (Pfrommer et al., 2013, Choi et al., 2010). Therefore, the semantic definition in domain ontologies and semantic data will affect the data representation formation, for integration of multiple manufacturing ontologies.

Semantic analysis techniques provide a great opportunity of converting the existing data into semantic data, which is standardised and in machine-readable formats. In order to support ontology sharing, the semantic technology is also applied in automated data mapping of ontologies.

3.4.1 Knowledge Transformation

In order to integrate PPR knowledge, capturing and representing semantic knowledge is an important step toward sharing machine-readable manufacturing ontologies (Montero et al., 2016). Based on semantic differentiation, several semantic transformation models were developed to evaluate ontologies meanings. These models are widely used in research and also in industrial projects for qualitatively analysing semantics contents, i.e. whether the content is positive, negative, and neutral. Formal ontology languages are used and developed to transform subjective knowledge into computer-readable data. For example, Frame-based languages are used to formalise lightweight ontologies (Lin et al., 2004), and Recipe-based languages using common logic to deal with heavyweight ontologies or complex semantic relationships (Agyapong-Kodua et al., 2014d). As mentioned in the previous section, the difference between lightweight and heavyweight is the complexity of the taxonomies used. Complex ontologies are not only increasing the complexity of semantic formalisms but also

increases the difficulty of interpretation by a machine. Heavyweight ontologies, therefore, should be limited to specific axioms and split into lightweight ontologies when possible, in order to improve the efficiency and accuracy of semantic analysis.

In terms of knowledge transformation, machine-interpretable ontology language will enhance the extending and sharing of ontologies between domains. As a result, rigorous mathematical modelling will help to identify different expressions of the same term and will allow to achieve and automate semantic-based comparison method. The knowledge transformation model must focus on transforming product, process, and resource knowledge into a semantic-rich data structure so that a scalable knowledge formalism can be created.

3.4.2 Knowledge Misunderstanding

Mismatched knowledge can occur at different cognition stages, such as communication between people, knowledge recording and also knowledge representation. Firstly, the cognition of the same concept is often similar but not exactly the same, especially when humans record these taxonomies. Secondly, different languages have different interpretations and expressions of the same thing. Thus, subconscious language logic has a certain impact on concepts' understanding. Thirdly, knowledge representation is affected by knowledge understanding and transformation. Repeated representation of knowledge will increase the complexity and diversity of knowledge compared to original knowledge. It has been acknowledged that simple information, which is passed from person to person is likely to be distorted. Because of the different understanding of logic, inaccurate correction, and repeated mistakes, a concept or a fragment of information may be changed to an even completely opposite meaning. Therefore, misunderstanding of knowledge can be classified as wrong knowledge extraction as well as differences in knowledge representation. According to the differences in knowledge representation, knowledge misunderstanding can also be distinguished by the semantic heterogeneity degrees.

There are two main semantic mismatches at the language level, which are called as conceptual mismatches and explication mismatches. Conceptual mismatches can be understood as the confusion of multiple concept types in the same domain. Due to the different ontology structures, the same ontology concept may be given a different definition with the same name. Additionally, related ontologies may also cause confusion in a given domain, and finding explication mismatches and correcting will be difficult. There are three different types of mismatch that can be defined as explication mismatches: paradigm difference, concept description mismatch, and encoding mismatch. In the manufacturing engineering domain, different paradigms can be used to indicate different concepts, such as machine state, cycle, process description, process step, etc. For instance, a production process can be expressed as a set of process steps, while another process might be refined into mechanical process states. Secondly, concept description mismatch is often described as different representations of the same concept. Several solutions can be used to solve conceptual logic modelling. As an example, different types of classes can be linked by a description attribute or by introducing communication class. Finally, different value formats are likely to cause encoding mismatches. For example, cycle time unit can be measured in second or millisecond. Thus, any of these three mismatches (paradigm difference, concept description mismatch, and encoding mismatch) or a mixture of them can be causes of the explication mismatches (López-Cózar et al., 2010). Negri et al. (2016) provided serval guidelines to solve the problem of manufacturing semantic misunderstanding. However, practical implementation and solution to the existing semantic misunderstandings problem are not provided. In order to promote semantic interoperability, semantic technology must improve semantic identification and correction of knowledge misunderstanding between different domain ontologies.

3.5 Automation Data Analysis

Product design depends on the iteration of the existing or new systems. Therefore, knowledge of existing systems is an essential component of the conceptual design process (da Silva et al., 2014). Moreover, Martin et al. (2013) have indicated that the usage of machine learning techniques and

multimodal reasoning could also help detect wide design methods and define behavioural models.

Additionally, some authors have attempted to utilise a three-tier architecture that integrates a historical knowledge platform with web server, built-in API and MS-SQL database management systems to support model design (Jong et al., 2013). A demand-driven knowledge acquisition system was also implemented based on the demand pre-processing, knowledge retrieval and searching (Chen and Chen, 2014). In order to solve this problem, ontology construction and ontology integration are considered to be the key technologies, as they allow to extract ontologies from design tool warehouses or dedicated websites and construct relationships of knowledge retrieval, searching and reasoning concepts (Vrba et al., 2011).

According to Hernández-González, et al. (Hernández-González et al., 2014), the ontology provides a standardised, formatted and structured knowledge description, with the benefit of being shareable, scalable and reusable. Ontology has the potential to become a key technology in enabling the extraction of engineering knowledge and the integration of engineering data management systems and software solutions (Ferrer et al., 2015a).

However, concept retrieval cannot meet all the requirements of production system design. For example, product designers currently do not have access to real-time reports on available manufacturing resources, during the design phase. Hui et al. (2007) mentioned semantic technologies, which provide and process data gathered from different customers or departments and give an opportunity of creating ontology-based systems to establish a real data-based semantic system. In addition, according to the semantic modelling approach, product information modelling is developed and applied by assembly planner in order to obtain the necessary product information and supporting the process design (Izza, 2009). Despite the increasing number of semantic tools and development of structural models, this area still faces a number of challenges, such as process prediction and appropriate resource selection with product changes.

3.6 The Gaps between Reconfigurable Requirements and Current System

Although there is still a gap between research and practical application of ontologies, academic research in semantic technologies has enhanced the productivity for manufacturing system design (Francalanza et al., 2014). Semantic modelling can improve information classification and management and increase product design knowledge. This means that semantic technologies offer a possible solution to answer the challenges of data, process and solutions integration in the domain of manufacturing systems' engineering.

Table 3-1 Current Challenges of Data Manipulation for Academic and Industry

Challenges	Academic	Industry
Data Acquisition	Data formats are not the same. A lot of information is a hypothesis or manually created (Mei and Ping, 2015).	Industry software is difficult to collect data (Gattani and Jafri, 2016).
Data Integration	General frameworks of integration data model. Low-level data is fragmented. (Tsoeunyane et al., 2019)	Data resource is various and integration has been developed on a case-by-case basis (Hufnagel and Vogel-Heuser, 2015).
Data Cleaning	Ideal situation for data cleaning. (Hamad and Jihad, 2011)	Uncertain or unexpected data are integrated into the centre database. (Kumar and Khosla, 2018)
Data Processing	Hard understanding of industry data structure. (Liu and Wen, 2015)	Different definitions for the same component; Misunderstanding of semantic transform (Yang et al., 2014)
Data Modification	Ontology technology is only used for query items. (Chinnathai et al., 2019)	Only few ontology implementations are using in the current industry. (Seyedamir et al., 2018)

Table 3-1 summarises current challenges of data manipulation processes including data acquisition, integration, cleaning, processing and modification. From the academic aspect, data are simple and clean for a specific situation. For example, processed data are generated by researchers rather than imported from existing tools. Automation related word and special vocabularies are clearly defined. Thus, results cannot extend to other domains or cases. Moreover, data modification is only made in the ontology editor rather than raw datasets. Without the ontology query, modified data cannot be imported into current industry software to evaluate their results. However, industry software is also typically lacks the capability to export data for academic usage. DELMIA only uses Visual Basic for Applications to generate Excel sheet or process data (Li et al., 2012). Unfortunately, the documentation for their automation APIs is not available on an official website, so this is a reason why software developers or researchers use processed data to manipulate data. Furthermore, inconsistent definitions are used for the same concept and even the same engineer use a different word to describe one actuator. To link this data, there is a request for semantic and ontology technologies. Semantic processing can clean industry outputs and automatically generate ontology. But current industry platforms do not make significant use of semantic and ontology technologies to avoid the need to redevelop existing data structure.

The use of semantic technologies has been partly applied in purchasing processes, assembly planning, and manufacturing systems integration. A large number of standardised vocabularies, ontologies and frameworks have been used in e-Procurement systems, and knowledge-based infrastructure has been used to simplify the management purchasing processes (Alvarez Rodríguez et al., 2014). Semantic technologies can provide and process data from different stakeholders while providing the basis to implement ontology-based expert systems. In the same way, based on a semantic modelling approach, product information modelling can be developed and applied in assembly planning to obtain the necessary product (assembly) information and assembly (process) design. Hui et al. (2007) used a three-level semantic abstract method to describe product information. They established an

information retrieval system by using Semantic Interpreter and Semantic Dictionary to obtain relevant information via different formats of technical documents. Furthermore, a set of service-oriented solutions was applied to the integration of industrial information systems by adopting the semantic/syntactic and dynamic/static methods. Ontologies are applied in industrial integration tools within Enterprise 3.0 and Web 3.0 to deal with semantic and meaning differences (Carbone et al., 2012). As a further basis for the use of ontologies, the semantic web has been applied in a commonly-deployed industrial technology within a wide range of programming community, including SMEs, OEMs and professional solution providers (Breslin et al., 2010).

Despite the increasing use of semantic technologies and structural models, some challenges still remain.

3.6.1 Rule-based Assembly Flow Design

Designing and selecting candidate manufacturing and assembly processes can be demanding if done manually. There is, therefore, a need for a systematic rule set to automatically help product designers to access assembly knowledge and therefore enable agile product and production system development with increased efficiency. However, there is a trade between the complexity of the information structure and system efficiency. Also, a core problem is that semantic models can be difficult for those product designers who are not familiar with product manufacturing processes.

3.6.2 Information Processing and Prediction

Current product design is using a top-down design approach, which breaks down product design into different subsystems. Sub-systems design is usually recreated detailed level systems to reduce system design time and improve the efficiency of system collaboration. However, a huge amount of data are generated during the design stage and there is a requirement that each data set needs to link with their first-level

subsystems. After all, sub-systems finished, information integration is a tremendous challenge for product design engineers. Additionally, current prediction models cannot find a relationship between product design and process requirements. Thus, process changes will affect each sub-system design.

3.6.3 Dynamic Information Analysis based on PLC Simulation Information

Most of manufacturing simulation tools are designed to reduce system cost and increase the efficiency of manufacturing development. To represent a real manufacturing system behaviour, virtual model simulates PLC communication and data blocks. Thus, a virtual simulation normally contains a logic engine to process inputs and outputs from PLC communication. However, incorrect manufacturing behaviour cannot locate a part of the code for PLC. Engineers have to check system processes and each actuators logic through debugging. There is a gap between dynamic information analysis and the related virtual simulation model. Based on PLC simulation data, information analysis should be capable of informing the user when faults have been detected. Hence, data collection and dynamic data analysis are required features for current manufacturing simulation tools.

3.6.4 Sensor Data Integration

With the development of sensor technology, industries sensors provide a lot of data and could be transferred to any IT infrastructures. In today's modern manufacturing environments, large amounts of time-series data generated by sensors deployed in the shop floor are recorded in manufacturing systems' databases. Due to the amount and irregular nature of these recordings (i.e. variable formats, lack of contextual or metadata, inconsistent readings, missing data points, etc.), data processing and data mining pose tremendous challenges. Information can be pre-processed by semantic models and divided into different data blocks in order to simplify the system indexes and queries. Semantic models with self-growth can expand semantic databases and improve the

accuracy of data analytics. Therefore, using the semantic model can enhance the robustness of the system by accumulating new knowledge to help product designers to solve new problems.

3.6.5 Manufacturing System Data Integration

Manufacturing systems engineering knowledge is obtained from past product and production system design iterations. This means that semantic knowledge should be applied to different product types in order to implement knowledge-to-application conversions. The primary knowledge integration problem is solving issues related to knowledge capture. Subsequently, similar but different concepts need to be established in order to improve semantic integration capabilities. The second important problem relates to system integration and the support of manufacturing system engineering throughout various organisation or engineering domains that use different software platforms and solutions.

3.6.6 Semantic Technology Implementation

The realisation of semantic technology is limited by the ability to analyse known semantics and identify unknown semantics. Existing semantic models can identify common sentences and paragraphs. However, semantic models are difficult to share across different ontology domains. To achieve product design and manufacturing system engineering semantic integration, specific formalism(s) of knowledge representation should be defined and developed by semantic analysis. As a result, advanced semantic technology could identify and address semantic mismatches between each manufacturing domains as well as clearly indicate the ontology relationships between each concept. Furthermore, the high performance and accuracy of semantic technology will be the key indicator of semantic analysis.

3.7 **Summary**

In this chapter, three manufacturing architectures are reviewed to discover the best practice for Product-Process-Resource integration. Firstly, Virtual

Factory Framework (VFF) describes a combination of product lifecycle and factory lifecycle. The benefit of this framework is to avoid repeated design work in both lifecycles using semantic technology. But low-level control logic is not explained in this method. In addition, process design and maintenance functionality are not easy to auto-generate without production knowledge. Secondly, the Sustainable Factory Semantic Framework (SuFSeF) is a middleware to integrate different manufacturing software in data represent level. This framework extended VFF model with ontology technology to create data structure of common manufacturing model. However, PPR data model is not described in detail. There is not a product design method related to process and resource data. Furthermore, the semantic query does not implement in this framework which means data representation is limited in basic query and it does not support knowledge generation. Finally, the Open Group's Architecture Framework (TOGAF) is a general framework to develop enterprise architecture which contains a design method for manufacturing systems, called Architecture Development Method (ADM). ADM provides a closed-loop to develop product or business model from information capture to implementation. This method linked each development stages with requirement management to fulfil objectives across the development stages as a whole. When requirements change, it is easy to locate related tasks or stages. However, ADM is still a general method for product development and TOGAF mainly focuses on enterprise development. Thus, this framework cannot guide detailed production design in the practice of knowledge integration. To avoid the disadvantages of the above frameworks, semantic technology has combined with requirement management ontology for automation data representation.

CHAPTER 4 **A Semantic-Ontology Methodology**

4.1 Introduction

In this chapter, a knowledge-based design framework is described to support a semantic-ontology methodology. The detailed system ontology design is presented to support the semantic part of this methodology. Product-Process-Resource-Requirement (PPRR) integration built the advanced predicting algorithms is explained at the end of this chapter.

4.2 Requirements for Integrated Knowledge-based Design

Based on the existing design methods analysis, manufacturing data have to import to one single application, which in order to support system analysis and simulation. However, different domain software cannot easily export or import data into one system, because of a lack of unified systems. A robust knowledge-based system integration methodology is a requirement of the current manufacturing system. To avoid the traditional manufacturing software errors, the following requirements are supposed for an integrated knowledge-based design:

- **Data Integration with same format and unified meaning.** To integrate different domain data, the knowledge-based system included product design model, process planning data, and available resource information. The data structure and format are used as a common data protocol for developing a reusable data manipulation function. In addition, product partial information linked with certain process sequences, and enhance the relationship between product components and process components at the knowledge level. At the same time, resource planning can be connected with the process step, and it will provide system capabilities of early product design. Modular design has considered for system development and improving system efficiency and data reuse.

- **Reconfigurable data structure for data reuse.** Decision-making model has the advantage of a knowledge-based system. As PPRR data

are analysed at the early design stage and all related data can be found based on the existing knowledge relationships. The first stage of decision-making model updated process and resource based on product modification, such as process sequence changes. The second stage is the evaluation of a new process to predict uncertain risks of next version system. The final stage is real-time prediction and decision making for resource changes. For example, a manufacturing system will automatically replace the shutdown machine with another available resource, and it can avoid serious production delay. It also reflected the changes associated with complex and varied processes, due to mechanical failure, lack of resources, increased workload, etc.

- **Automatic modification for process planning.** Smart component query supported semantic search, which includes the related information searching, similar component suggestion, and rapid nature language analysis. Nature language searching is the most difficult task of a knowledge-based system. As all data have been translated to semantic data and then the system can analyse the basic natural language to link PPRR data with customer search. Due to the uncertain customer request, a smart component query has structured into object with optional parameters at the very beginning. For example, customer can search product component with same process sequences or find physical machine with certain product features.

The proposed methodology, which also called an ontology based semantic model, is used for rapid product design and manufacturing system simulation.

4.3 Overview of the Framework

This framework uses a systems simulation tool to collect product, process and resource data, because systems simulation could easily reflect any changes related to system processes. Collected data are translated to semantic data and imported to the ontology environment using this framework. All data modifications are finished within a JAVA-based user interface to decrease the level of ontology understanding needed by its users.

To model the interdependencies and predict the impact of changes, there is a need for understanding the process, resource and requirements implications of product changes and vice-versa. The rapid reconfiguration of systems depends on the specific domain knowledge, expanding semantic database and building new product modules with shortened product development cycle. In terms of the PPRR model, each module's knowledge is independent and stored in the corresponding space.

Data acquisition is the first step of collecting data from the independent database or file system. Typically, the manufacturing reuse data process is a closed-loop, including files locating, data import, data modification, Product-Process-Resource validation and new data generation. Files locating and data modification require an understanding of project architecture, such as related processes planning, existing product requirement and the location of previous files.

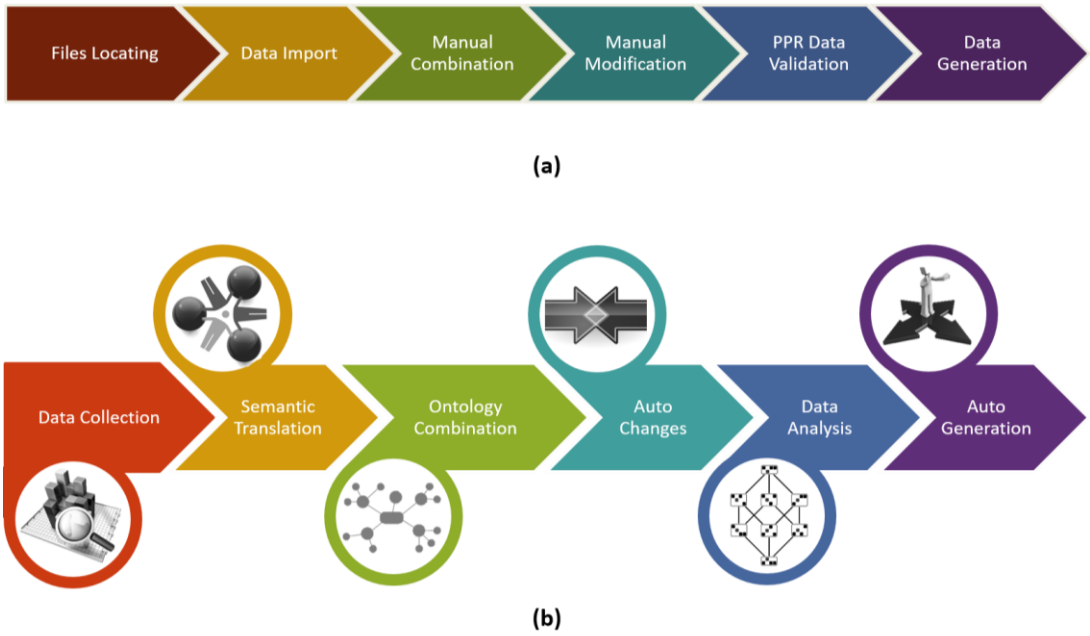


Figure 4-1 Data Process Flows: (a) Current Data Reuse Processes; (b) Proposed Data Flow

Figure 4-1 shows a new data process flow that starts from data collection to decision making compared with current data reuse processes. Data collection will gather all the relevant data and models from manufacturing systems,

which might contain different formats, languages, even file types, etc. In order to accurately extract the knowledge, semantic translation is an important step of defining suitable concepts, categories, and domains by using semantic technology. Then, the data combination will check the existing knowledge library and add new knowledge to expand the existing information system. Meanwhile, knowledge integration reduces redundant data, and it helps massively to save data analysis costs and decrease the ontology mapping difficulty.

Ontology mapping will take the advantages of ontology and semantic technology, and it can achieve automatic linking to data with the ontology structure of a rule-based relational knowledge model. Furthermore, reasoning engines can attach unknown logic and relationships to a known knowledge system, which to analyse possible changes and related restrictions. A well-built rules development, therefore, will be completed by the experienced engineers in product design, process assembly, and resource planning areas. In the previous industrial system, decision has been normally made by human by using their knowledge and emotion. This increases the risk of decision making and the difficulty of decision making. However, through the analysis of the existing models and data, intelligent engineering integration, it will provide a reliable decision-making suggestion based on the existing requirement changes and available resources. Besides, ancillary decision-making system will reduce the cost of decision making and knowledge requirements of decision-makers.

The vueOne virtual engineering tool, which is developed by Automation Systems Group in WMG, University of Warwick, supports virtual simulation for automation assembly systems using component-based design method (Alkan and Harrison, 2019). It is a new generation of lightweight system integration tools, which was called the Core Component Editor (CCE) toolset (see Figure 4-2). CCE toolset provides a powerful 3-D simulation engine and it simulates manufacturing process with a minimum cost and also integrates product, process, and resource.

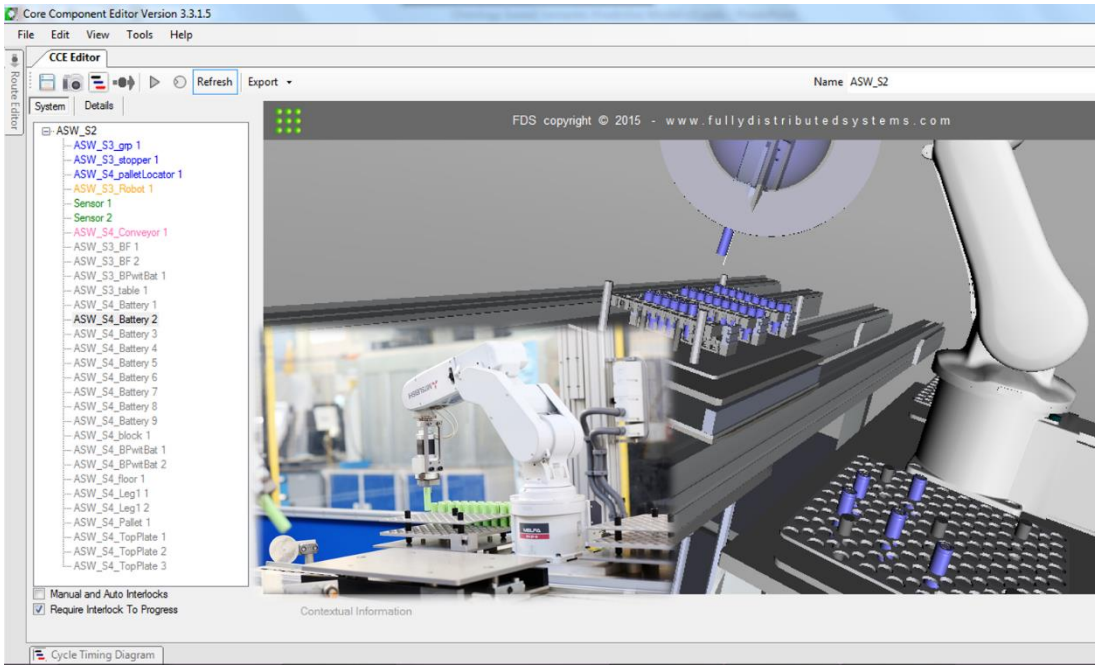


Figure 4-2 vueOne Manufacturing Tool

Thus, it is a suitable platform for achieving a new generation of industrial solutions. However, vueOne tool is only for achieving lightweight system integration. For example, it uses Virtual Reality Modelling Language (VRML) for system simulation and process planning functions within reusable component blocks of automation assembly library (Ahmad et al., 2016). VRML supports lightweight 3D modelling viewer in web-browser, but a heavyweight 3D modelling is difficult to edit and even hard rerun in VRML format (Satish and Mahendran, 2017). Additionally, the product import and model export follows the traditional data storage models, recognised based on a specific attribute (product type or concept classification). However, it cannot distinguish the same product with different expressions like product name or file name. Furthermore, there is no logical relationship among the products, processes and resources when all processes are imported. Due to this, process engineers have to manually provide the process states, transitions, and conditions with each product and resource. This is a common problem of most of manufacturing software. DELMIA also integrates a large amount of industrial data and has achieved a knowledge-based manufacturing process model (Neamţu et al., 2012). But a lot of manual processes and industrial knowledge background are still needed to be done by engineers, such as

importing product models, changing related process sequence and updating resource availability. Manual processes not only delay the process design cycle but also increase the possibility of making a mistake during manual operations.

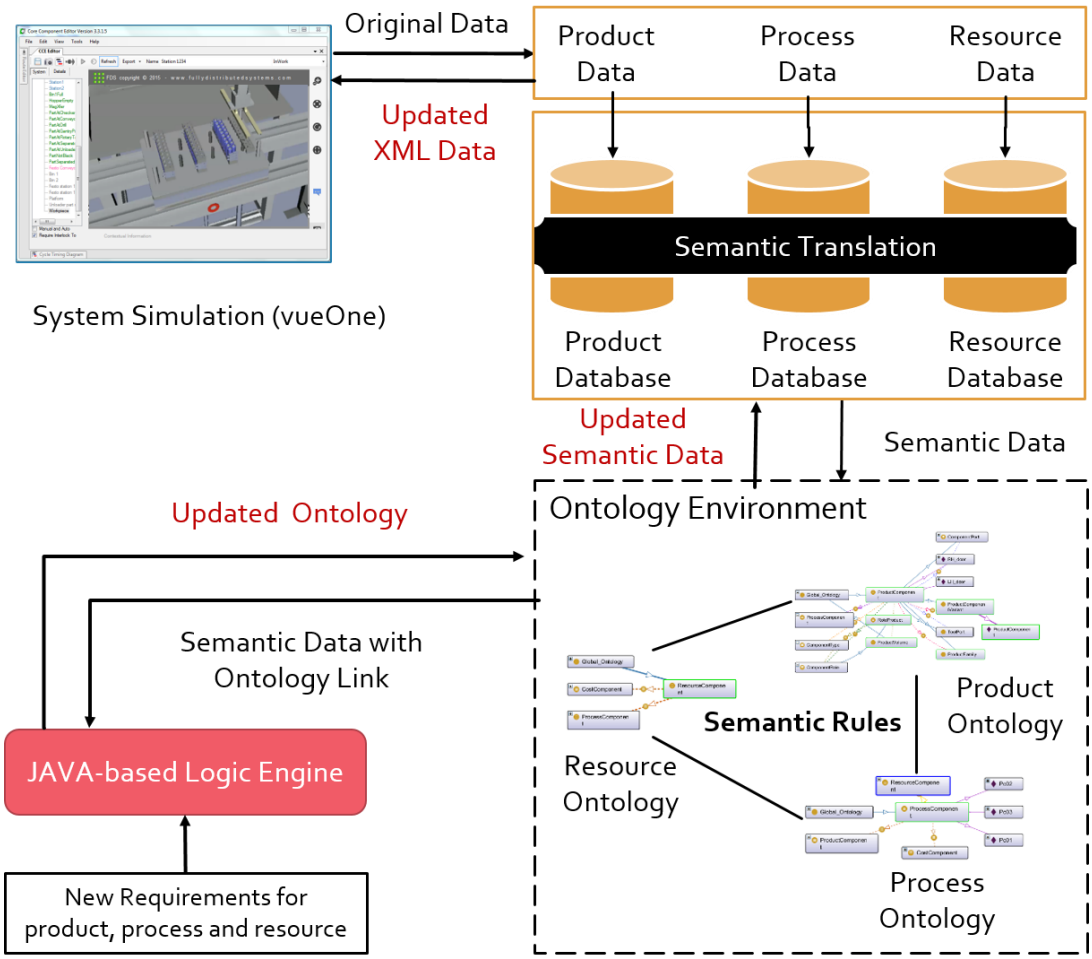


Figure 4-3 Ontology-based Semantic Data Integration Framework

Figure 4-3 shows the proposed framework of the ontology-based semantic data integration including the PPRR data transformation, semantic database with ontology mapping and rules-based model. This framework supports the existing simulation model reconfiguration. The semantic translation model translates the simulation model of an assembly system to semantic data, which can be uniquely recognised. After mapping semantic data with ontology, product data is linked with relevant process and resources data. Thus, each change in the product model will automatically link with relevant process and resource data. During product requirements changing, the rules-based model

can modify PPR semantic data and update the XML file (simulation model) automatically. As a result, required changes can be carried out in the simulation model but without manual modifications.

In this framework, each knowledge system contains a specific set of contents including process plan database, available resource data and product model knowledge. For example, a product model contains process knowledge, and it can be found via the previous process design library. Resource knowledge generated by the established resource models contains process models and vice-versa. All the knowledge can be retained by the inherited methods, and the knowledge also will be enhanced by updating iteratively manufacturing system modelling science. Rapid reconfiguration is not just a re-combination of the old model, but also a generation of new products, processes, resources, and requirements based on previous knowledge.

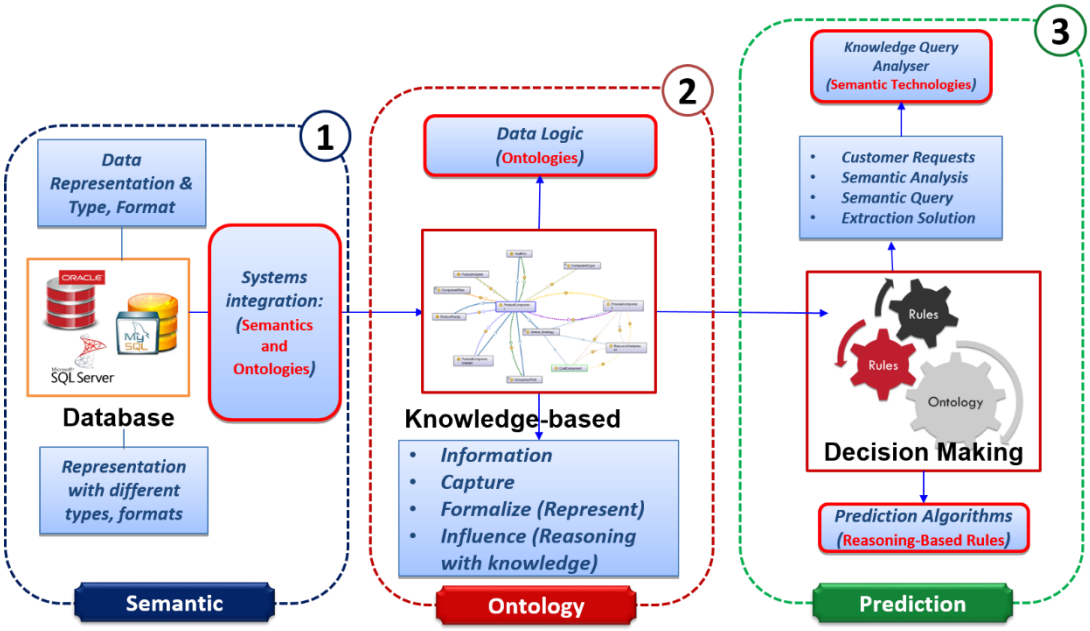


Figure 4-4 Key Technologies for Semantic-Ontology Model

Figure 4-4 shows the three key technologies for the framework, including semantic technology, ontology mapping and rule-based data modification reasoning. Semantic technology gives data meaning and ontology mapping processes data to a PPRR structure. The last part uses a rule-based algorithm to modify related data and generate updated files.

Firstly, semantic technology is used for data manipulation, including data collection, processing and cleaning. Before integrating different database, data representation should have the same formatting and type. Semantic transformation can process data into the same representation for the same meaning data. For instance, *PART* is equal to *UNIT*, *PIECE* and *ITEM* when those words describe product structure. Hence, all words transform into a unique word for further analysis.

Secondly, ontology technology place data into pre-defined data logic (i.e. product, process, and resources relationship) based on the semantic category. A knowledge-based reasoning analyses data relationship and provide data influence for data analysis. For example, battery-package contains a battery cell and a battery plate. So battery cell should link to the battery plate to match battery-package model.

Finally, the modification engine uses a pre-defined product-process-resource algorithm to make process changes based on product or resource change. A rule-based reasoner is applied to semantic data to identify variables' relationships. In addition, customer query can be separated to link data logic, such as product library with related process steps.

Based on a cross-platform systems integration requirement, the framework can analyse an entire production process plans well as evaluate the suitability of different products. By splitting the production process and process flow analysis, the production process can be transferred from the process design software to a process simulation platform. Warehouse, resource and cost information are also transferred and combined in modelling software. Digital simulation framework should obtain an appropriate control logic and basic information, as a result, a process flow chart is displayed on this platform and can be easily modified to accommodate the unexpected plan. All software connected to this framework will be able to automatically update data and system status. However, there are still some practical challenges in place, especially when implementing integrated 'Intra or Inter Information Systems'. This is because systems are designed without detailed consideration of levels of integration. However, they are required by enterprises (product-process-

resource interconnections) for file transformation, data formats, manipulations levels, specifications and representations. Thus, a semantic transformation model is necessary to maintain the correct meaning and suitable formatting, during the data transformation period in different systems.

4.4 Manufacturing System Structure

Due to the advancement of computer-aided product development, industry is looking for other alternative ways of accelerating product development and reducing the costs (Wu et al., 2015, Wang and Wang, 2014). Hence, a knowledge-based system integration architecture is presented in this research. The main elements of this manufacturing integration system are Human–Machine Interface (HMI), CoTS software and semantic modelling. The manufacturing systems integration architecture is represented. By integrating hardware devices or sensors, users will only need to provide product descriptions and technical requirements.

The manufacturing integration system can automatically select the appropriate suppliers and manufacturers for customers. The user may be looking for a cost-effective supplier, or an SME, which cannot afford to produce complex parts or even an engineer who has some innovative ideas. The knowledge-based manufacturing concept is introduced to enhance the ability of concurrent design and to build up an internet-based platform for product design so that relevant product-process-resource (P-P-R) knowledge can be established via a semantic ontology system by using the Web Ontology Language (OWL)/Resource Description Framework (RDF).

However, knowledge-based architecture is often used during the distributed hardware systems integration, but distributed software systems or semantic logic systems can also be applied in knowledge-based manufacturing. The manufacturing integration architecture is consisting of: (1) Client-side, (2) Server-side, and (3) Telematics centre as shown in Figure 4-5.

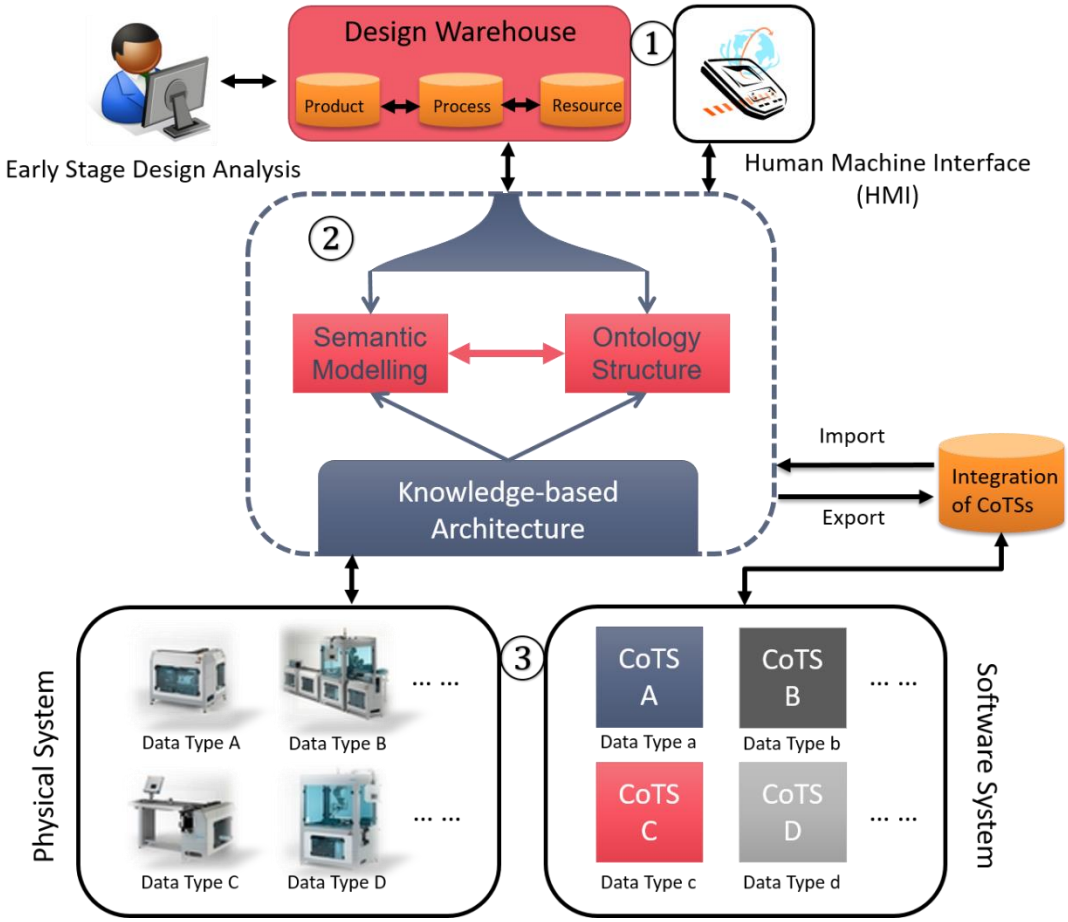


Figure 4-5 Manufacturing Systems Integration Architecture

(1) Client-side includes design warehouse and Human Machine Interface (HMI). At the early design stage, product designers can get real-time product design assistance and Key Performance Indicators analysis from design warehouse. It combines three main components including product database, process database and resource database. These data are not only stored in a separate database, but also connected to a rule-based semantic model. User requests are semantically decomposed into computer language to achieve accurate data retrieval. For example, “What is the available process in the next step of the ProcessA and the costs is minimal?” will be broken down into “SELECT ?process ?cost WHERE (?process processlib: nextprocess “ProcessA” ^^xsd:string .; ?process resourcelib: has_resource ?resource .; ?resource resourcelib: has_cost ?cost)”. HMI is a prescribed user interface, which is directly connected to the server. Due to the input restrictions and standardised query, objective data can be quickly found

from the server and all the latest data, so users do not need to worry about data updates or data backup problems.

(2) Server-side contains semantic modelling, predicting algorithms and knowledge-based Operating System (OS). Knowledge-based architecture (shown as 2c) is a foundation for the entire system and used to support analysis of information, logical operations, and data storage. According to user requirements, system applications can be deployed on different hardware and software environments. Moreover, user can scale processing capabilities from 10 to 10000 by a quick click and this change will be updated in a few minutes. The configuration and load balance to the server security will be visual editing in the client, and the server then will ensure the safety of the entire system. Semantic modelling (shown as 2a) and predicting algorithms (shown as 2b) can be automatically deployed on the server. Ontology-based data integration application will unify the data structure and standardise the format.

(3) Telematics centre comprises a physical system and software system. Physical system integrates all available devices and sends real-time data to the server via a wired or wireless network. In addition, the transmission system does not use any complex logic or standardization of data format, because the equipment or sensors do not have large storage devices and data analysis processor. To reduce costs and increase the system's compatibility, optimised hardware system will only require data acquisition and upload devices. Software end usually includes data export functions, so data processing part can be done in the software system. By integrating COTs, a unified format data will be sent to the server, so the server can directly process the data meanings through semantic analysis model to save cycle time.

Due to different data types associated with hardware and Commercial of the Shelf (CoTS) tools, a scalable and extensible semantic model is introduced to integrate and help to classify and process data. By integrating hardware devices or sensors, users only need to provide product descriptions and technical requirements. The knowledge-based manufacturing systems will automatically and intelligently, such through suites of databases and select appropriate suppliers and manufacturers resources via the design warehouse.

This will inevitably support the assessment of product designs at an early stage. As previously mentioned, some users who are expecting the supplier can be more economic, but then these suppliers might unable to process complex component or lack creative engineer. By adapting the knowledge-based architecture, it will help them solve this issue as well as provide sufficient production capacity.

As this approach is aiming to reduce product design time for young engineers and some designers, especially people who are not familiar with assembly planning and resource information. By establishing a flexible design module, it can integrate useful databases in support of design and manufacturing, designers also can be equipped with more robust and dynamic modelling tools. By doing so, knowledge-based manufacturing technologies will help achieve the objective of low prices, fast processing speed.

4.5 System Ontology Descriptions

A common engineering understanding is that products (P) are realised by processes (P) which consume resources (R) and which depend on requirements (R). Therefore, there is the need for understanding the process, resource and the cost implications of product changes and vice-versa. The rapid reconfiguration system depends on the specific domain knowledge. They can be reused to facilitate machine learning, expanding the semantic database and building new product modules, with shortened product development cycle. In terms of the PPRR model, each module's knowledge is independent and stored in the corresponding storage space. Moreover, resource knowledge generated by the established resource models will contain process models and vice-versa. All the steps of knowledge are connected with the cost model. All knowledge can be retained by the inherited methods, and knowledge can be enhanced by updating and iteratively using manufacturing systems modelling science. Rapid reconfiguration is not just re-combination of the old model, but also the generation of new products, processes and resources based on the previous knowledge.

According to recipe-based semantic modelling methodology (Agyapong-Kodua et al., 2014b), authors built up a rapid reconfigurable semantic methodology for supporting product design during the product lifecycle early stages. Via semantic modelling techniques, user requirements can semantically be matched with derived knowledge from products-process-resource configuration library, and it is pre-defined and pre-processed. Finally, the user will get some detailed information about currently available product models, process planning suggestions and resource situations. Moreover, every advice and system solution will be presented via an intuitive visualisation interface.

The details of the ontologies are provided in the subsequent sections.

4.5.1 Product Ontology

Product ontology is the basis of the conceptual framework of manufacturing systems design. It describes the product components and structures and establishes a suitable logic for product design. Product components can be broken down into smaller units and these smaller units then will be classified to be reused for new components. Product structure can be considered as the relationship of providing accurate contact information or suggestion. In previous studies, the product connection was used as a product components attribute. With the increasing product complexity, assembly contact will become complicated and difficult to be handled. As a result, reducing data query and improving data editing efficiency can be a matter of urgency. To balance the system efficiency and logic readability, the connection with new product components is retaining immediate family of products. A product component includes “products, sub-assemblies, and product family” within the product domain. A contact component holds “products, parts and units” within the relationship domain (see Figure 4-6).

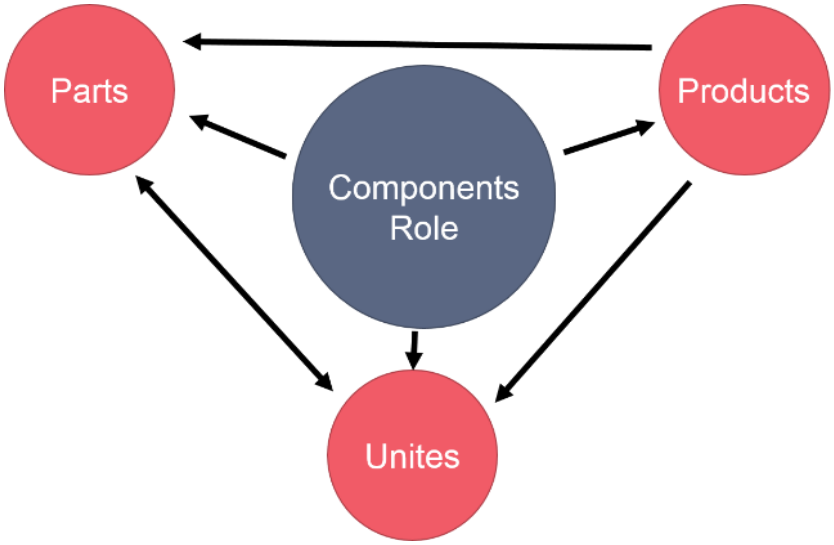


Figure 4-6 Contact Component Description

The product semantics modelling is divided into several subsystems, and it includes external design, structural design and materials design model. In manufacturing systems design, most exterior designers will focus more on fashion and beauty of products, whiles product engineers often consider the structure and performance attributes of products. Thus, if the exterior design model is embedded in product design knowledge, exterior designers would not have to understand the product structure's principles and this will minimise design time.

4.5.2 Process Ontology

The process ontology describes process definitions for realising products. This ontology is an important link within the manufacturing systems design, as it combines the production system and product design attributes altogether. Product demand analysis automatically considers the product characteristics to determine the process design. Hence, the process semantic model filters out some corresponding workflow solutions through the known relationships and related databases, and then designers can choose the best option.

In the process domain, different activities are modelled to establish appropriate groupings. When a new part uses the same conceptual design, processes of needed capabilities would be selected. Also, low-level activities

are coupled to form top-level processes. As a result, designers do not have to consider all the process details.

4.5.3 Resource Ontology

The resource ontology formalises the definition of resource attributes in the manufacturing systems design. It has three main considerations, which includes equipment machine, human resource and factory layout. A system usually runs on several machines and has different input parameters, size, and productivity and so on. Different plant or equipment suppliers can use completely different database and development software. Semantic model can help industrial systems integration and classify these data sets. The human resources component describes information needed for workers, such as technical requirements, work type and position restrictions. In order to find suitable workers, human resources ontology establishes relationship with process ontology and equipment machine ontology. The system reconfiguration layout is a concept of possible layouts. After a selection of equipment and human resources, the system can match the appropriate layout and changeable parts with system reconfiguration.

4.6 **PPRR Capability Integration**

Semantic modelling usually processes large amounts of data and relationships from the ontology engine. To improve the processing efficiency and queries accuracy, a separate domain ontology is established, as one of the main ontology with a contact ontology to avoid accessing unnecessary results.

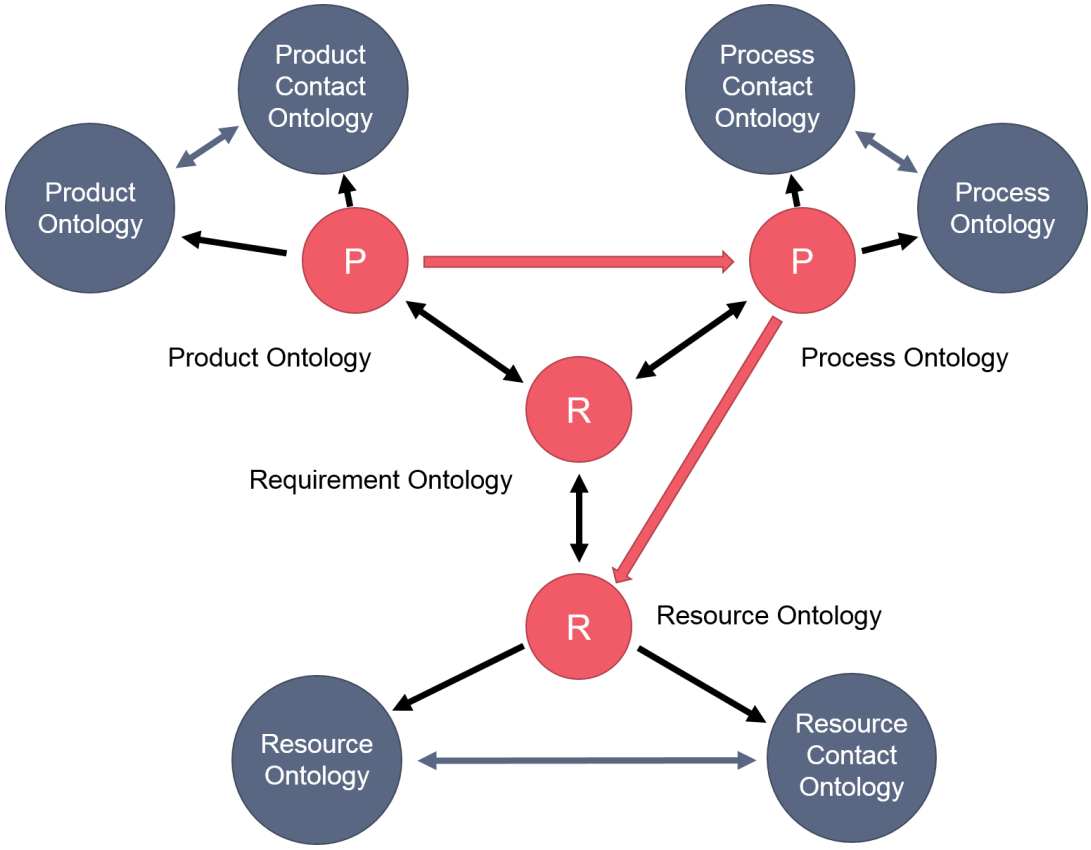


Figure 4-7 Integrated Ontologies Architecture

Each domain ontology establishes independent 'attributes' and the ontologies with the same type or similar semantics can share one public contact ontology as a 'relation'.

Queries can be applied in the sub-domain ontology (blue circles) to obtain a specific parameter or integrated ontology (purple circles) to check related data. The integrated ontology is achieved by linking with different contact ontologies that in the different manufacturing system components - product, process, resource and requirements (see Figure 4-7). Through the semantic model, the information is logically extracted and optimised. The end results could be displayed through visual models or virtual reality technologies to improve editing efficiency.

4.7 PPRR Data Transformation

As mentioned above, semantic data transformation is important to increase system reliability, but the current process simulation system cannot analyse data meaning and relationship between product, process and resource.

Furthermore, the changes in a product cannot directly reflect the processor resource change. This is because product, process and resource data are stored in a database without meanings and relationships. According to traditional product design methods, process (P) are linked with the product (P) and resource (R). Resource and process's requirements (R) limit the product's functions and features. Figure 4-8 presents the traditional process simulation steps in vueOne including process development, mechanism design, concept design, model design and process simulation (Chinnathai et al., 2019).

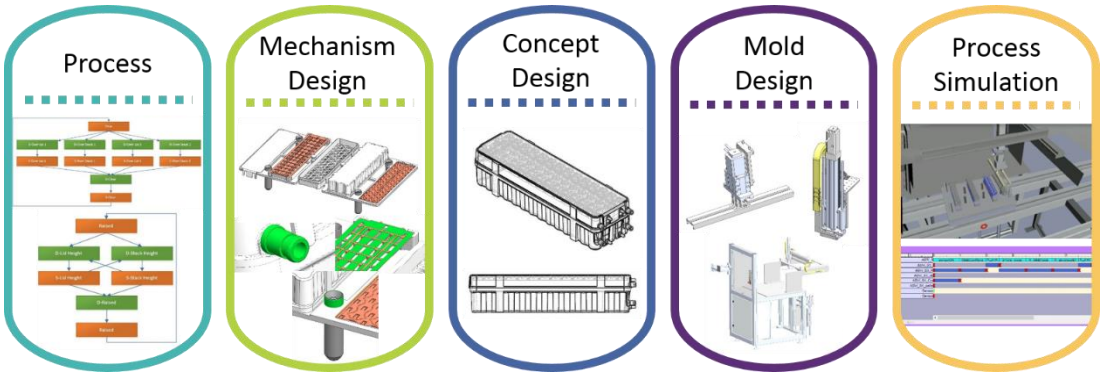


Figure 4-8 Process-based System Simulation (Chinnathai et al., 2019)

Ontology-based modelling can build the link between different databases and predict sub-link or product design solutions, by using Pellet and HermiT reasoners. In addition, such modelling requires an understanding of process, resources and cost implications of products changes and vice-versa. Furthermore, PPRR integration is finished in one system to bridge the gaps of formalising data in different applications.

4.8 Semantic Database with Ontology Mapping

Typically, ontology-based system depends on specific domain knowledge, but that knowledge cannot be reused to facilitate machine learning via a set data dictionary. To address this, a semantic data model can be used to improve the accuracy of ontology-data mapping and enhance system robustness. Integrated semantic technology and machine learning algorithms can potentially expand the scope of product design knowledge as well as the semantic capabilities of data analysis. Semantic technology can translate designers' questions and customer demands from human language to

ontology languages, such as OWL/XML or RDF/XML. Furthermore, system server derives available product models, manufacturing process plan suggestions and resource situations, via semantic mapping of PPRR configuration libraries.

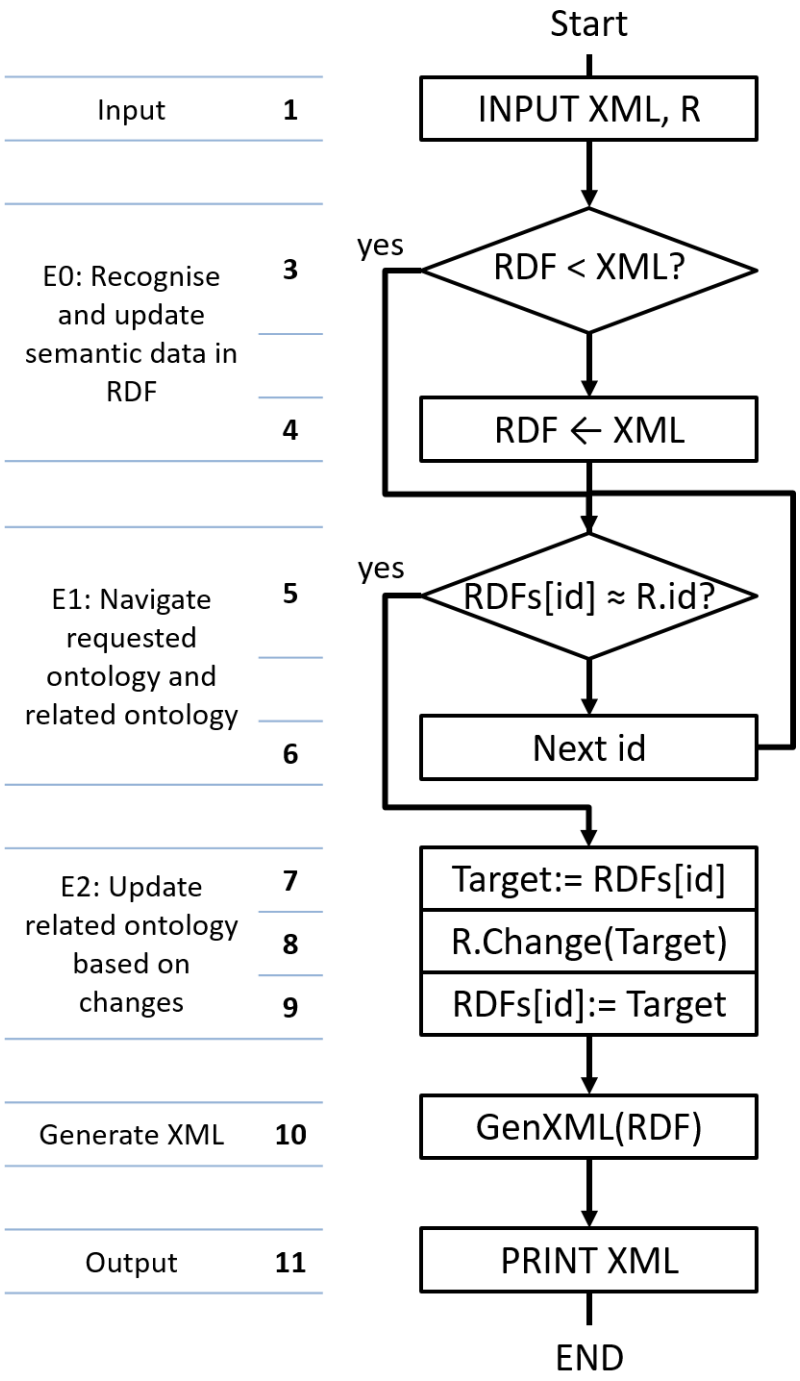


Figure 4-9 Ontology Mapping and Auto Generation

Semantic transformation model handles ontology mapping and auto ontology generation (see Figure 4-9). XML file as a user input import to the model for recognising and updating semantic data in RDF. The model navigates request ontology in Step 5. If the knowledge cannot be recognised in the current ontology, function block will check next related ontology until the correct record found. Step 7-9 are updating related ontology based on customer requests. A new RDF file will be created after all changes finish. The output of the model is a new simulation file for vueOne tools.

As previously mentioned in Section 4.6, there are separate ontologies to help semantic modelling can avoid accessing any unnecessary outcomes. Especially, when it processes the data and relationship imported across engines. Through the semantic model, the information is logically extracted and optimised. Furthermore, the end results are displayed through visual models or 3D based virtual modelling tools to improve the system design and reconfiguration process.

4.9 Rules-based Model

As described above, process simulation links with product, resource and requirement information, so the model focuses on building the relationships among process-product, process-resource and process-requirement. For example, griper open process is linked to the griper CAD model and griper movement sensors. Moreover, griper open speed and opening stroke are both included in griper requirements, which means process change directly affects resource planning and requirement. Also, the available resource of current automation system restricted the usability of process design and product design. During resource changing, some appropriate modifications are made in the process and then final product design is directly reflected by process change. In that case, changes of the process requirements (ΔProcess) are closely linked with resource changes (Δresource) and the constraint of process requirement (ΔRequirement) is the main problem of a new product design (ΔProduct). PPRR changes structure is demonstrated in Figure 4-10.

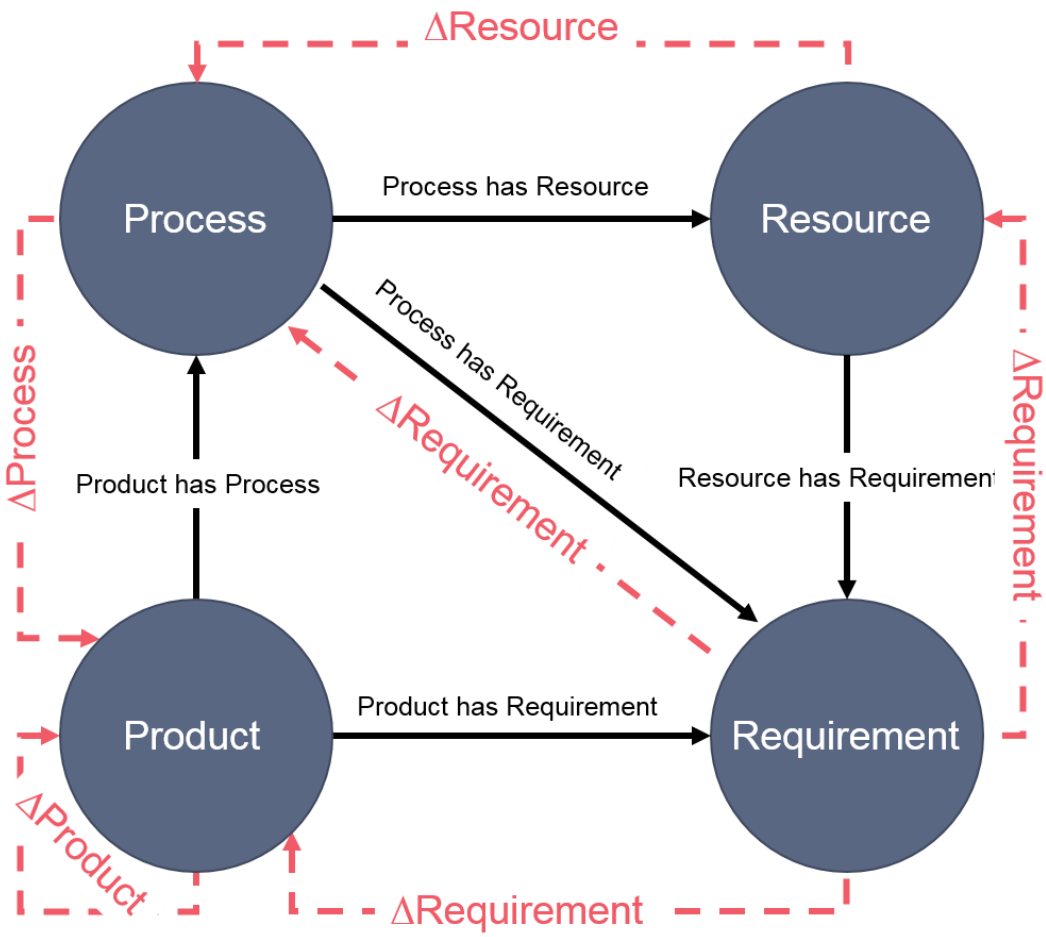


Figure 4-10 Product-Process-Resource-Requirement Changes Structure

The basic data elements within the proposed framework are product, process, resource and requirement. Product has a couple of processes and requirements from the customer. If product requirements change (ΔRequirement), some product changes (ΔProduct) apply on product, parts or units. Due to the relationship between product and process, product changes affect process sequence or a part of the process (ΔProcess). In addition, the process has process requirements. If process requirements change (ΔRequirement), process and product need to update in the meantime. On the one hand, resource belongs to the process. On the other hand, resource has requirements. Thus, any changes in resource requirements (ΔRequirement) cause resource changes (Δresource) and process changes (ΔProcess). In summary, one change in any domain requests a couple of modification in process planning and simulation, because all elements within the proposed framework are linked together.

Another important aspect of the semantic model is the future prediction. According to the law of information conservation, this model uses a decision tree to predict any available processes and a suitable manufacturing system design model. It is on the basis of requirement change such as cycle time, material and costs. Those parameters are marked with different rank, and it helps the prediction system to evaluate all processes via currently available resource.

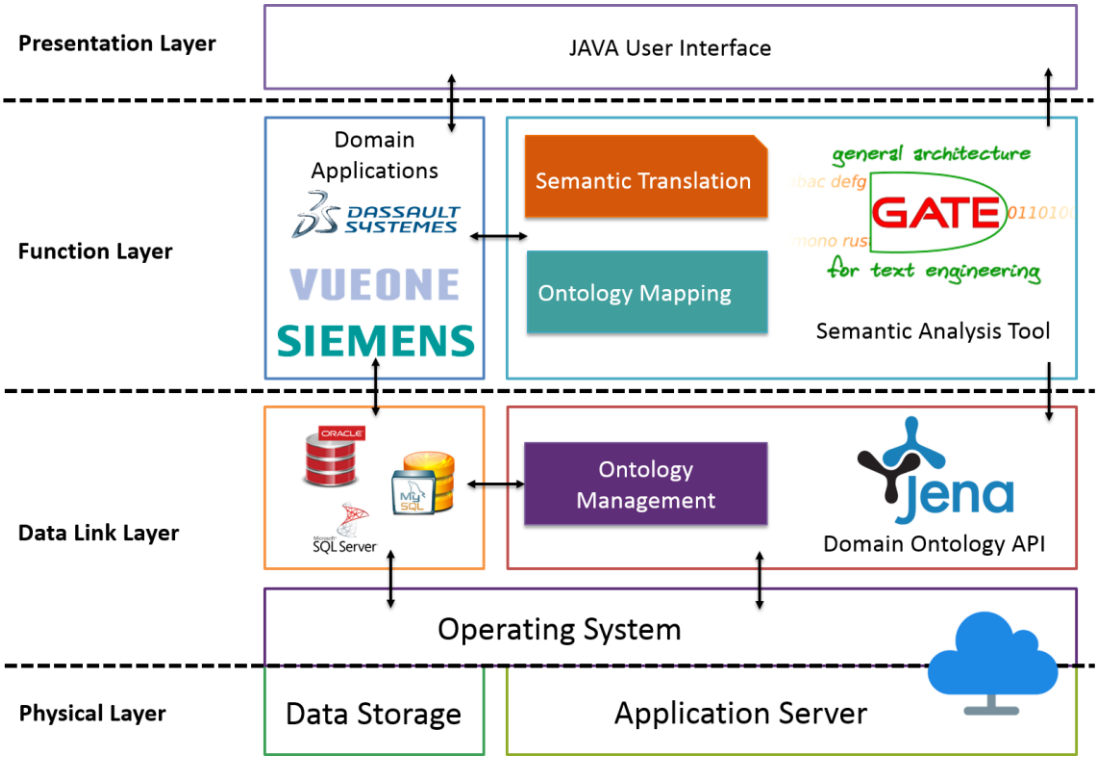


Figure 4-11 Ontology based Semantic System Architecture

However, calculations will become very complicated if different decisions have restriction or uncertain links. A semantic-prediction model can transfer data into a rule-based ontological structure, so the system can choose an optimal solution from system ontologies to avoid conflicts. As a result, the model not only predicts requirement changes in the next phases but can also determine the valid system design that meets the product requirements. The system architecture contains four layers including presentation layer, function layer, data link layer, and physical layer (see Figure 4-11). Firstly, data storage and application server are located in the physical layer which can store in any cloud service. The Data link layer manages database integration and domain

ontology API which uses Apache Jena framework. In addition, the operating system, which can be a virtual machine on the cloud service, is in the middle of software and hardware. All manufacturing development tools are based on the function layer. GATE uses semantic technology to map information with a predefined ontology structure. End-user can only see presentation lay which implement by JAVA-based user interface. To decrease the requirements of ontology-based semantic system, a command-line user interface (CLI) is implemented in this research. For procedural commands with multiple parameters, CLI is more efficient than a graphical user interface (GUI) (Feizi and Wong, 2012). Moreover, CLI supports basic functions of data manipulation to assess the Semantic-Ontology Engineering Framework. In addition, it is unnecessary that users should understand ontology and semantic technology for using the PPRR ontology model.

4.10 **Summary**

In this chapter, knowledge-based automation system's requirements are defined in three aspects. First, data needs to integrate into the same format and unified meaning. Next, a data structure should be reconfigurable for efficiency of data reuse. Last, the modification process can change PPRR data in one query to optimise process planning. Comparing with tradition data reuse processes, the new proposed data flow features updated data import, combination, modification and validation processes to automate methods. The vueOne virtual engineering tool is used for system simulation and process planning. Thus, the proposed framework uses vueOne tool to integrate product, process and resource data. To achieve automatic data processing, three key technologies are used for the framework, including semantic technology, ontology mapping and rule-based data modification reasoning. Semantic technology gives data meaning and ontology mapping processes data to a PPRR structure. The last part uses a rule-based algorithm to modify related data and generate updated files.

System ontology describes product-process-resource relationships and descriptions for each domain ontology. To improve the PPR ontology model, a requirement ontology is developed for linking product, process and resource

ontology. PPRR data structure creates a possibility to modify process planning based on product and resource requirements. To reuse existing data in a new ontology model, semantic translation formats data to the same structure and a unified meaning for the same concept. In addition, semantic technology is also applied to automatic ontology-data mapping to enhance system robustness. Moreover, rule-based model addressed synchronisation issues of data modification with multiple requirement changes. One requirement change affects related product, process, and resource changes and updates can be done in one step.

Ultimately, ontology-based semantic system architecture describes four layers for the proposed framework. The physical layer contains data storage and application server for all physical devices. The data-link layer is based on the operating system and it could use Jena API to manage Oracle, MySQL or SQL Server databases. Additionally, domain applications are located in the function layer and GATE handles semantic translation and ontology mapping processes. The final layer is the presentation layer which demonstrates data modification functions using JAVA-based user interface. In the next chapter, implementation of the proposed framework is presented with details ontology definition, semantic analysis and automatic data generation.

CHAPTER 5 **Implementation of Semantic-Ontology Engineering Framework**

5.1 **Introduction**

This chapter presents an ontology implementation and natural language processing method for automation systems integration. Based on the description in section 4.5 of CHAPTER 4, global ontology contains product ontology, process ontology and resource ontology. Firstly, product ontology is described as product configuration class which has a component type, component role and product configuration. Secondly, process ontology is classified into process type and activity. Lastly, the topology of a resource is defined based on the resource and process relationship. Furthermore, detailed ontologies are also explained in the following sections. The rest of this chapter demonstrates semantic transformation processes and document processing implementation. A vueOne data processing structure is introduced to support information identification, ontology dictionary mapping and auto ontology generation.

5.2 **Global Ontology**

A product design is used and all requirements are entered into the case study. Based on the methodology in CHAPTER 4, the global ontology is defined as the following ontologies: Business Case, Component Role, Component Type, Process Component, Product Component, Cost Component, Delivery Method, Liaison, Liaison Type, Product Volume, Required Test, Resource Component, and Scenario (Figure 5-1).

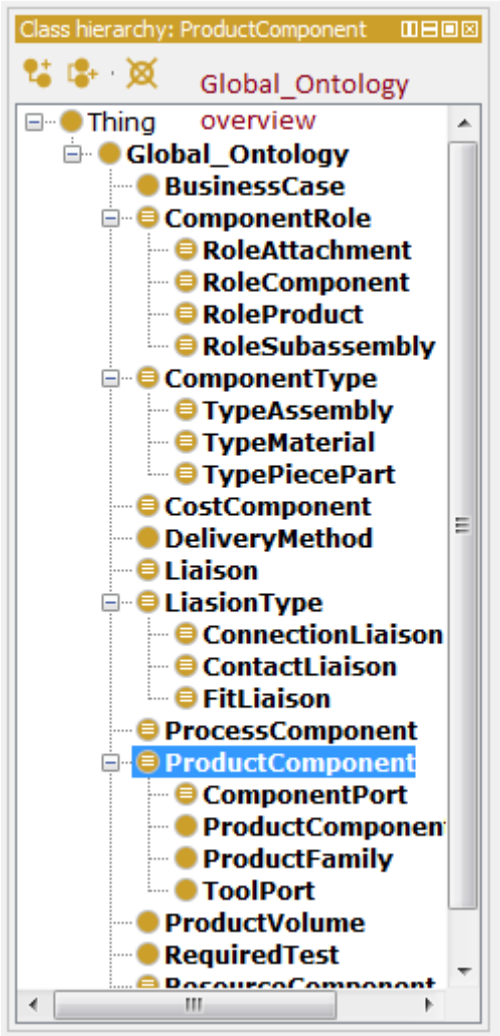


Figure 5-1 Global Ontology Overview

The Business Case contains all the automation systems and business logic for each automation system, and it is also a human-readable index of global ontology to help ontology developers to find the correct ontology library and instance.

The Product ontology describes the details and concepts of business case and product specification under the manufacturing system framework. The Process ontology explains the process definitions and process requirements for each process step.

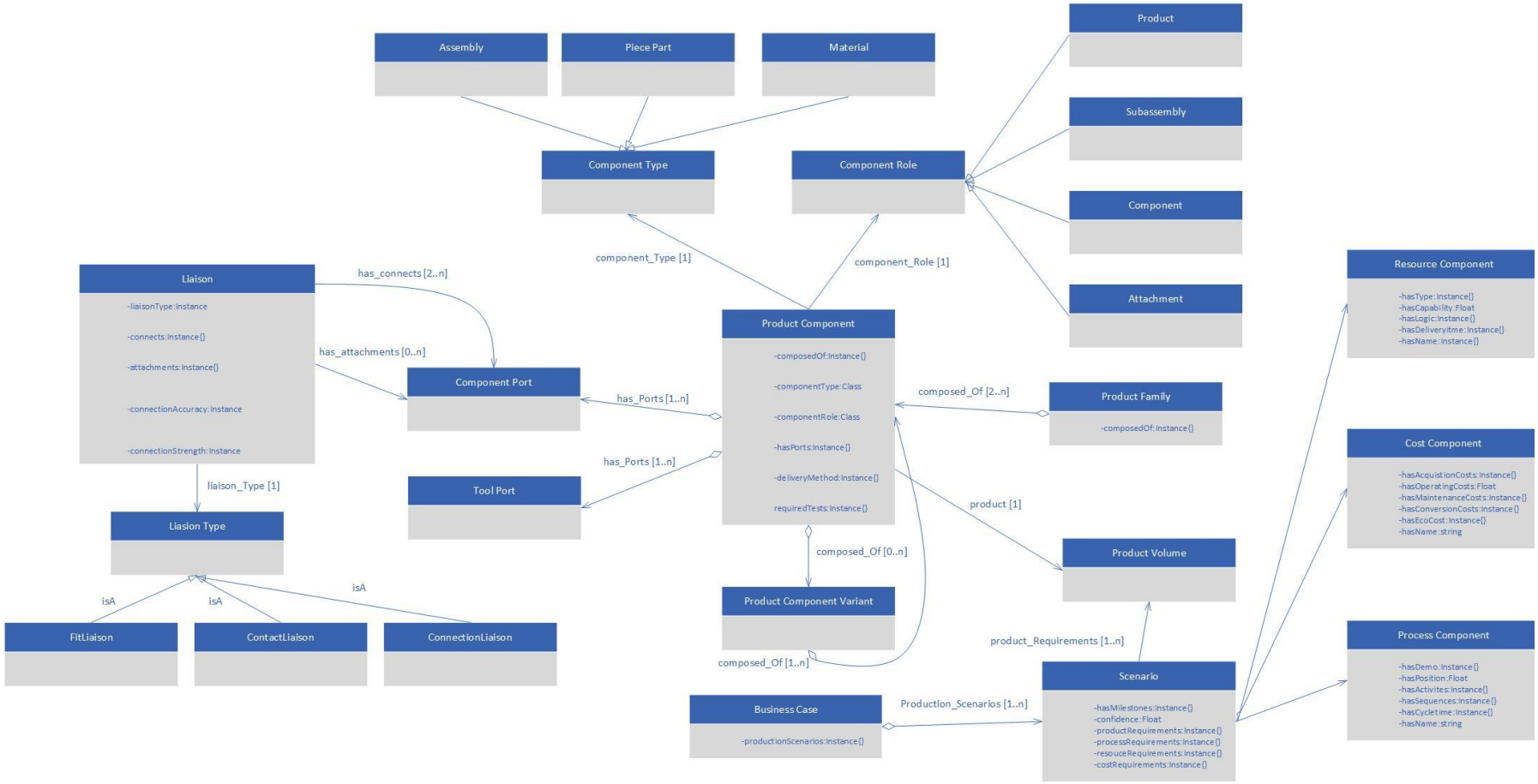


Figure 5-2 Product-Process-Resource Ontology Architecture

Moreover, the resources ontology is to outline all the available resources and the capability of models with specific manufacturing process requirements. However, more detail of these ontologies will be covered under the next section. Figure 5-2 shows the links between product, process and resource ontology.

5.3 Product Ontology

The product ontology includes all product features that relate to product design, type, and production relationships. The most important parts in this ontology are, the explanations of physical product features which include production requirements, parts assembly and related component relationship. In addition, the product ontology is built up with a simple classification, which related to product configuration, component role, and component type. With the purpose of enabling faster query, a well-structured organisation formation is requested to represent all physical products and related parts within the product domain. Figure 5-3 shows a hierarchical structure of product domain to display product ontology. The Product Component is at the same level as the Business Case ontology in actual ontology.

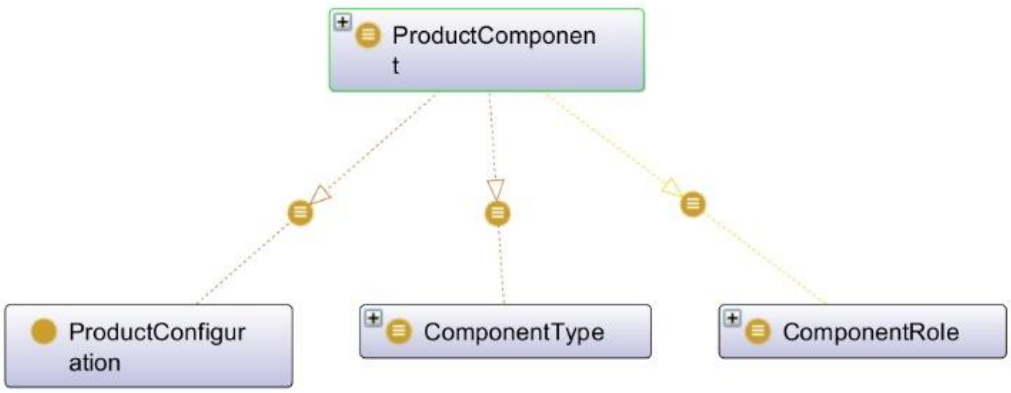


Figure 5-3 Product Top Ontology

The Product Component has three hierarchical relationships including *has_production_configuration*, *has_component_type*, and *has_component_role*. The Product Configuration defines the relationship with liaisons ontology; the Component Type describes the different physical types

of product components; while the Component Role explains the functional aim of a product component.

5.3.1 Product Configuration

The Product Configuration is a link to generate the relationship between a product and sub-parts. The relationships in the Product Configuration can be classified by the type of connections including Contact Liaisons, Fit Liaisons and Connection Liaisons. Those three main Liaison types are defined to describe different production components' connections and further classification can be found in Figure 5-4.

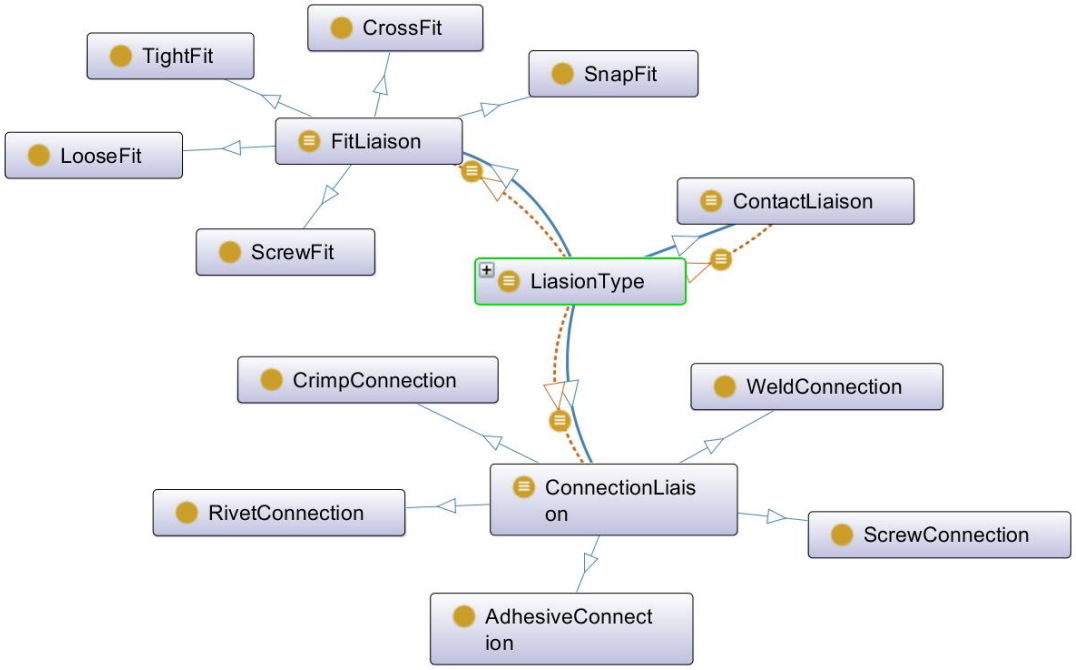


Figure 5-4 Liaison Type Classification

The Contact Liaisons outline the physical or geometric connection that relates to a link point connect and surface connect. This Liaison can be changed by a product engineer and the results will affect the process sequence and process details. Additionally, the most basic Liaison has a limited capability to help process decision making.

The Fit Liaisons describes interactive mode between two product components and assembly method of each element, such as a round hole and a work piece.

Therefore, a Fit Liaison is more specific and accurate type, by comparing with a Contact Liaison. Although multiple Contact Liaisons may have the capability to achieve the same meaning of a Fit Liaison, the expression of a Fit Liaison is at a further presentation level of the relationship between the product components, rather than a combination of Contact Liaisons. For example, drilling a round hole in the centre of the work piece is representing the process level of product component design, which could help a process engineer or auto process tool to generate detail processes based on a simple Fit Liaison.

The Connection Liaisons form a triangle connection relationship that contained two main Product Components and a third piece. This type of Liaisons is the most complex relationship and the process of each Connection Liaison is fixed, and cannot be replaced by another process sequence. The third element will be defined at Attachments in a Connection Liaison, such as laser or screw. This Liaison has the scalability and a high degree of adaptability for future case study.

5.3.2 Component Role

Beside of the Product Configuration, the Component Role is another important ontology to describe the purpose of a product component. This ontology can be split into five components, including *Role_Product*. *Role_Product_Family*, *Role_Subassembly*, *Role_Component* and *Role_Attachment* (see Figure 5-5). In one scenario, a product could be the subassembly for another process component. A metal component, for instance, is a subassembly of the work piece at the Handling Station, and a product at the first assembly stage. Thus, the product component role is a specific attribute for a product component in a certain case, and it could be changed in different scenarios.

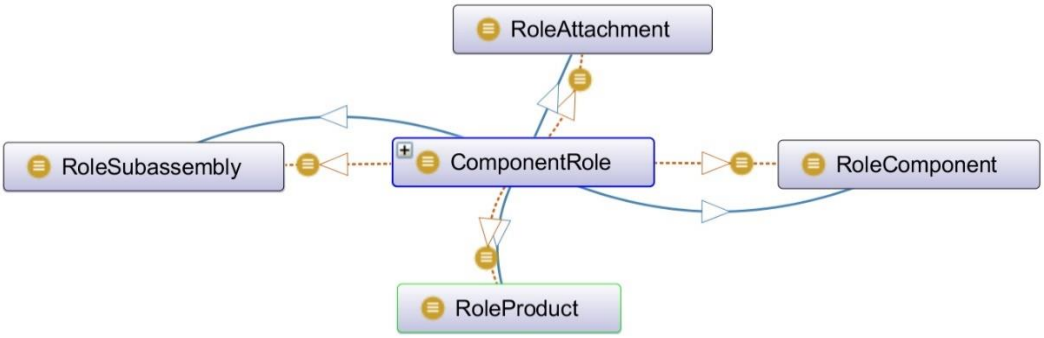


Figure 5-5 Component Role Classification

The following rules are the implements to define the Component Role in Festo Didactic Test Rig Assembly System:

- A product could be one of an original concept, model and physical block to use in a specific process, such as a work piece in the Festo Didactic Test Rig. A work piece is produced by a sold part and it is the main piece part in whole assembly state.

- A subassembly defined a related part or material for assembly purpose. The metal hat, for example, has a physical connection with a work piece and it is used to detecting a sensor for the Handling Station. On the other hand, the subassemblies are defined as a part of assembly processes, such as B-Pilar inner for the welding process.

- A component is developed for a complex assembling system, which contains subassemblies and product as a whole component for further assembly process. They could be processed by inter production matches or directly delivered by a third party manufacturing supplier.

- As the part of Connection Liaison, an attachment is a certain material or work part which can join two product components to one single component. For instance, the attachments could be a screw, adhesive, or weld solder etc.

Based on the Component Role, a product concept can also be another products' family. Figure 5-6 describes the relationship between product components and different component types.

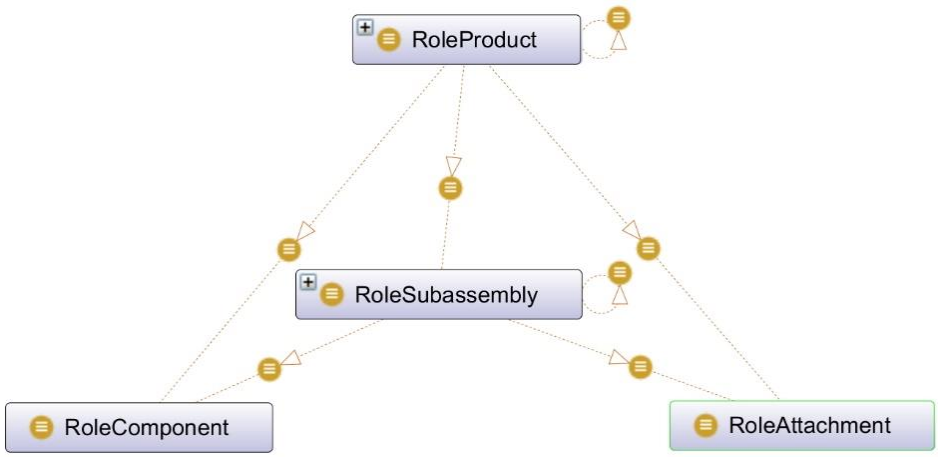


Figure 5-6 Component Role Relationship

A product as the highest level of product components can be connected with Role Component, Role Subassembly or Role Attachment, but may not include any other product components. A product could contain two or more Role Components or Subassemblies with any combinations. Moreover, attachments can only be contained in a product, which needs to join two Role Components or Subassemblies.

Furthermore, the Role Subassemblies can also contain other Role Components, Attachments or even another Subassembly. However, Subassemblies must connect at least two other Product Components, because this is the only difference between Product and Subassemblies. But Components and Attachments are the basic elements in Product Components, so they cannot include any other product components. Hence, a Product Component can be described in a different context by using component rule or component type in one specific situation. In one of test case, a work piece is defined as a Component at the Handling Station, but it would be described as a Product for the whole Festo Didactic Test Rig System. For the Handling Station, the internal structures of the work piece will decide the right container,

but the whole system will focus on sequence definition rather than product structures.

5.3.3 Component Type

The Component Type describes the physical features and product relationship between different product components, whilst the Component Role outlines the manufacturing logic of a product component. For an assembly sequence, one assembly product at least has two sub-components, which could be an Assembly or Piece Part or Material. The hierarchical relationship between product components is showing in Figure 5-7.

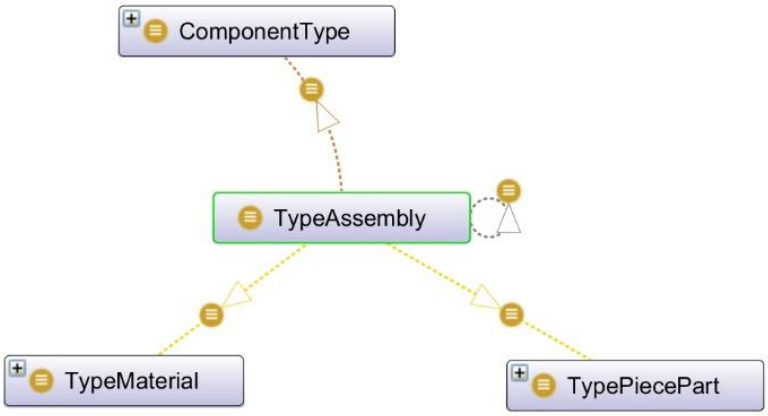


Figure 5-7 Component Type Classification

Piece Parts and Materials are the lowest level of assembly products, so they can only belong to an assembly or other product components, and as a basic elementary entity in the Product domain ontology.

5.3.4 Detailed Product Ontology design

The Product Component includes Component Port, Product Component Variant, Product Family, and Tool Port (see Figure 5-8). Moreover, it is described using *has_componentType*, *has_processComponent*, *has_composed_of_productFamily*, *has_componentRole*, *has_toolPorts*, *has_productVolume*, *has_componentPorts*, and *has_composed_of_productComponentVariant*.

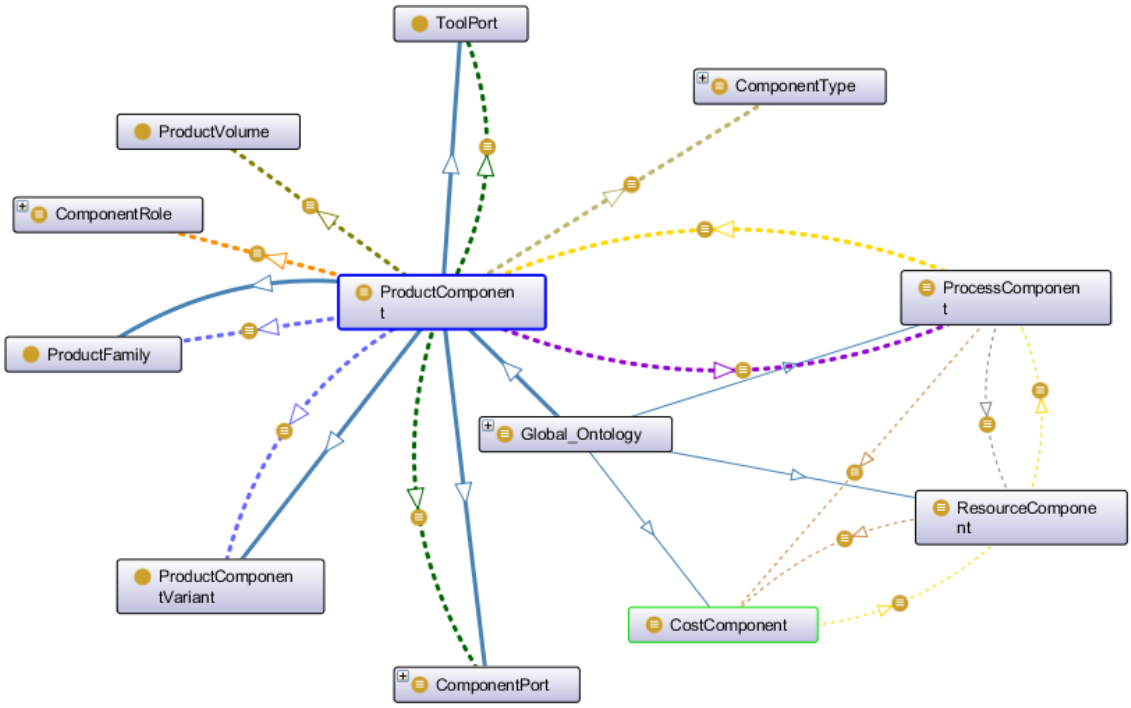


Figure 5-8 Detailed Product Ontology Design

5.4 Process Ontology

The Process ontology describes the product processing or assembly processes under the PPRR conceptual manufacturing framework. The Process ontology is also a key component between the product and resources, to bridge the gap between process simulation and real manufacturing system. The fundamental concepts of the Process ontology are defining required processes, and they are based on product characteristics and available resources that could achieve process requirements. According to business requirements, product specifications, and some limitation on manufacturing environment, new or reconfigurable manufacture should be developed by certain rules or constraints. It could be translated into an ontology-based semantic relationship. A product usually can be built by one or more possible processes to achieve the same characteristic. Which means the manufacturing system could use different resource based on the process requirements. The Process ontology should contain all the possible process for each manufacturing system and create a link between each process and

resources. Each process also should include a series of different process constraints for meeting the product requirements.

5.4.1 Process classification

The Process ontology can be classified into a few hierarchical levels by Process Type and Activity, which then define the multiple process concepts into other different levels (see Figure 5-9). Process structure is organised in a hierarchically way, to provide a clear view for a process planner and improve the performance for ontology reasoning. Hierarchically relationship is to enable an effective way of organising complex processes into a group process to avoid multiple connections with a single part or resource.

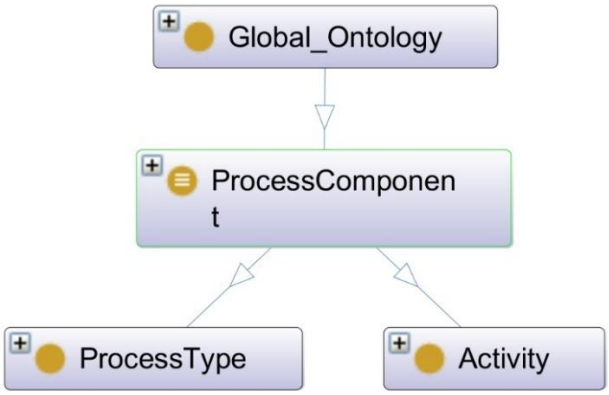


Figure 5-9 Process Classification

Process Component is the highest level of process ontology, which could contain one or more Activities, and they are the detailed process steps or actions for each process. Based on the top of process concept, a process planner may develop the whole process model for each product and it is easy to show the model on a 3D simulation tool. As it may not need the detailed information in process steps. However, Activities are more focusing on the process parameters, such as location, cycle time, speed etc, and containing one assembling activity that includes all assembly or subassembly process.

5.4.2 Process Activity

The Activities are regulated through other four high-level activities, including Actions, Operations, Tasks and Multi-tasks (see Figure 5-10). The following rules are to define each Activity and sub-ontology types:

The Actions are basic activities to describe the processes for an operator without product assemblies and changes, such as product movement, delivery process or part loading.

The Operations describe building blocks of machine processes and product status changes by the equipment. Moreover, Operations may contain a set of actions.

The Tasks contain all process related to, for example, workstations or transport systems. This clear definition of product requirements and detail processes.

A multi-task is the highest level of process component, and it includes different assemblies, subassemblies and production progress. Additionally, multi-tasks define the system blocks, which link to a task, operation and action.

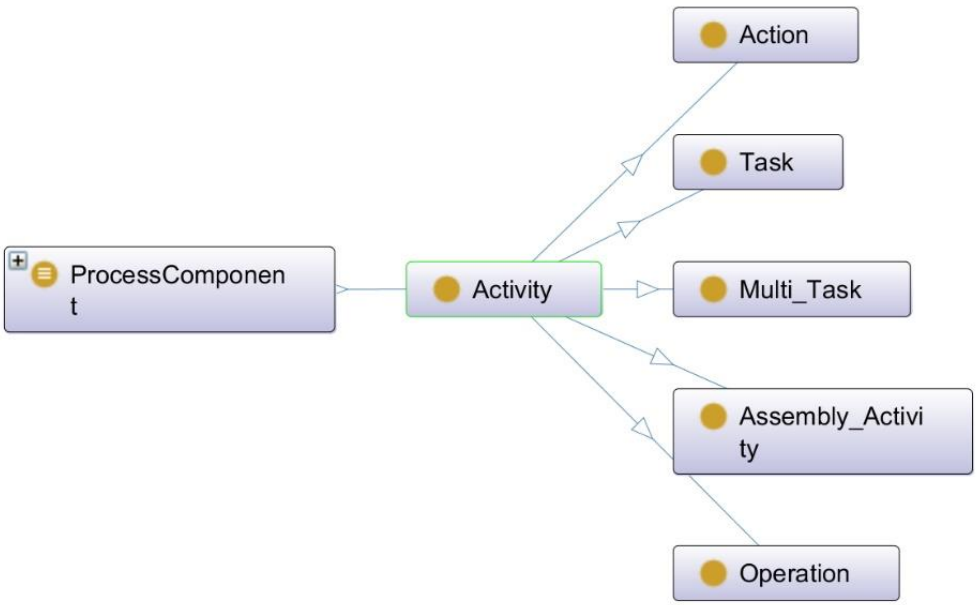


Figure 5-10 Activity Component

The relationships between an assembly activity and individual activity have been described into the ontologies, as showing in Figure 5-11. The Assembly activities include operation and request tasks, which may also comprise multi-task ontology.

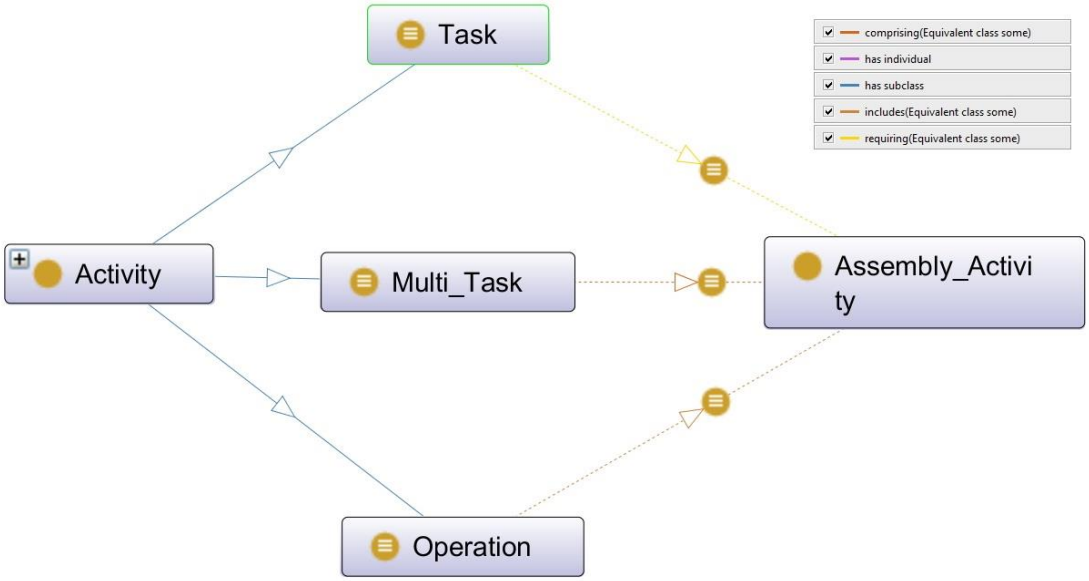


Figure 5-11 Assembly Activity Relationship

As the methodology defined in CHAPTER 4, the Process ontology should have a fixed relationship with the Resource ontology. Thus, the Activity will be the bridge between processes and resources. To enhance the structure and scalability of PPRR ontology, processes link operation system for code generation and process control. The relationship between two ontologies is defined by *responsible_for* attribute of resource ontology. In the case of Test Rig, the Distribution station can be responsible for 2 tasks, but a work piece is responsible for multiple operations.

5.4.3 Process Types

The Process types are designed to describe process stages and detailed phase attributes, and they are including Production, Assembly, Storage, Packaging and Support (see Figure 5-12 in details)

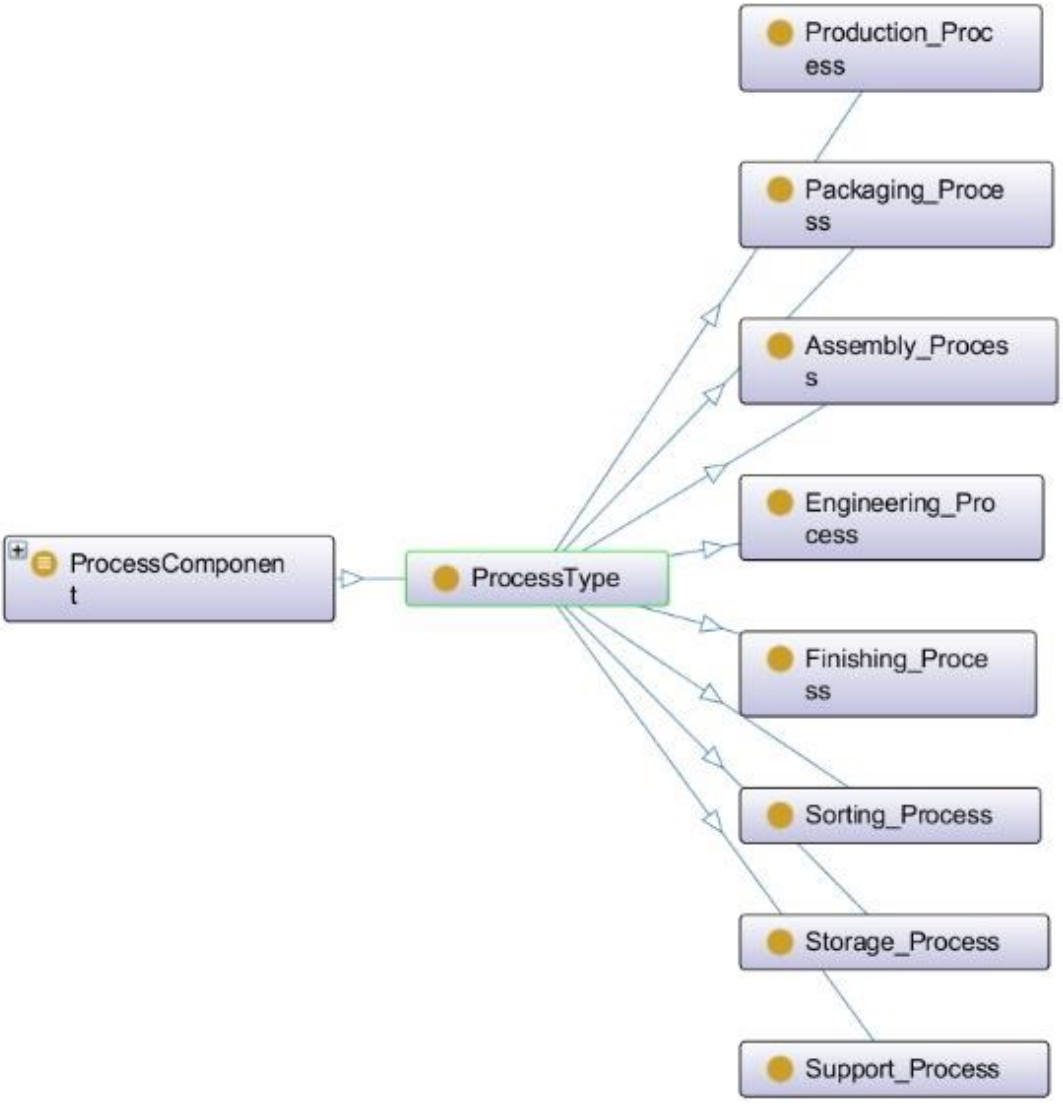


Figure 5-12 Process Types in the Process Ontology

The relationships between assembly process component and sub-level components are demonstrated in Figure 5-13. The Assembly process defines a part of the assembly category, which includes glueing, welding, screwing, arranging, force-fitting and soldering.

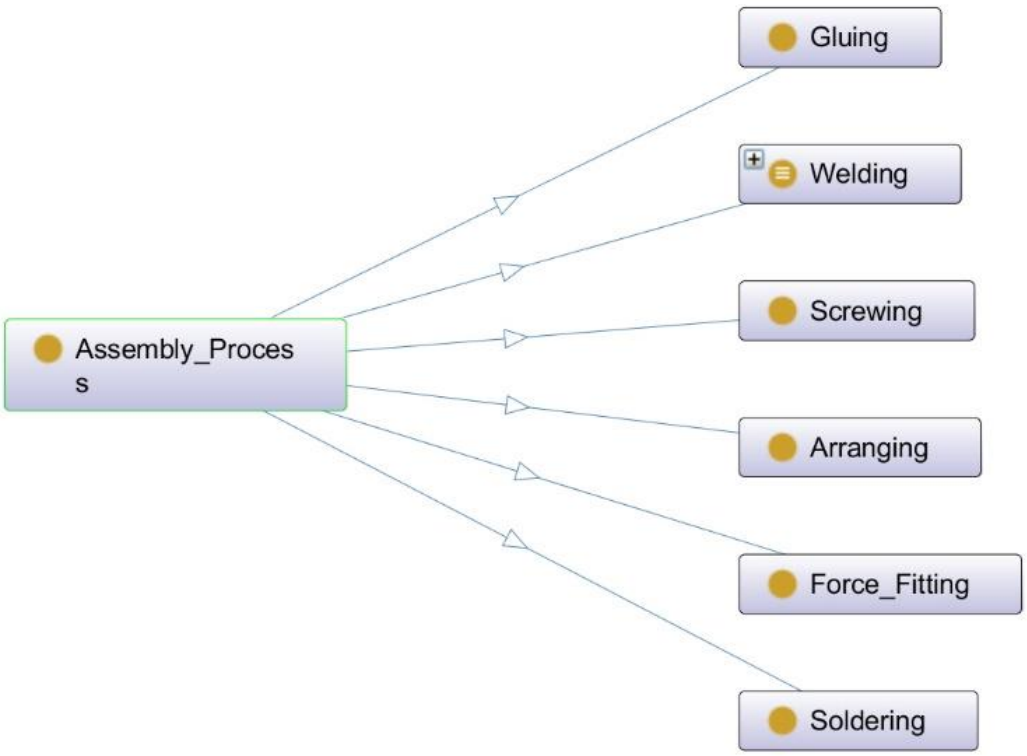


Figure 5-13 Assembly Processes Component

To establish a relationship between the Process ontology and Resource ontology, resource units are usually attached to the Process ontology as requested equipment. For instance, a car door assembly can be achieved by a laser welding machine (see Figure 5-14). Meanwhile, Product ontology also has a relationship with a detailed process component.

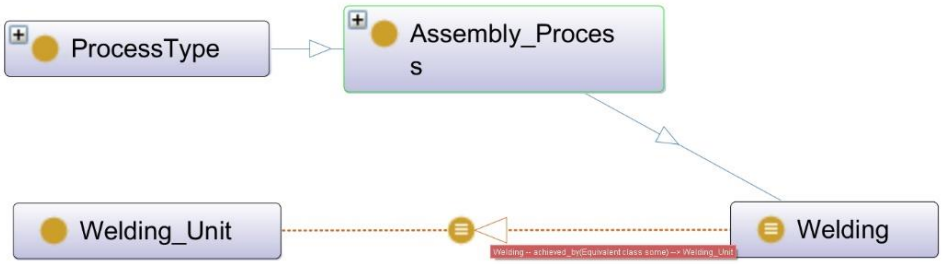


Figure 5-14 A Relationship between Welding Process and Resource

Engineering process describes the typical product development process through prototype to implementation. In this case study, there are a couple of engineering processes, which are involved to test the model. Figure 5-15 shows the structure of the Engineering Process ontology.

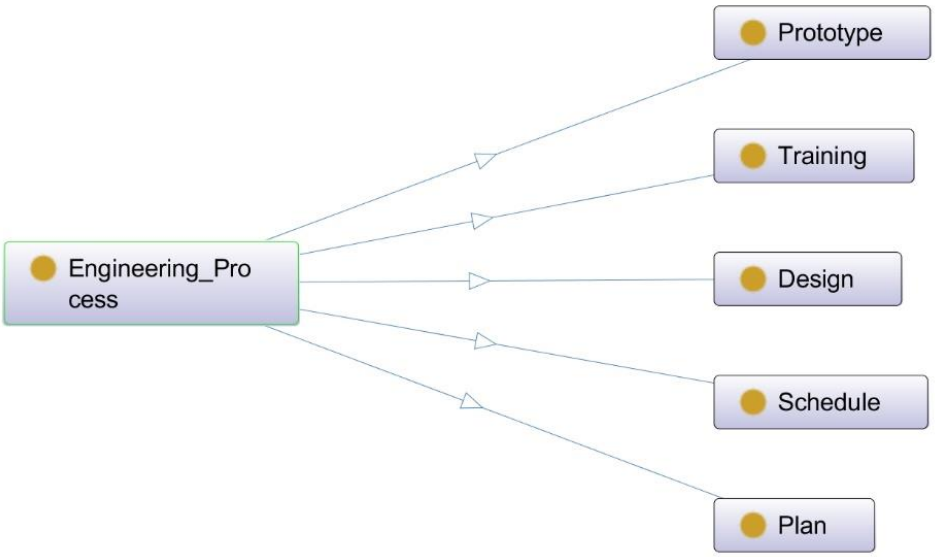


Figure 5-15 Engineering Process Classification

To complete production lifecycle, Finishing Process ontology has been created and the main finishing process methods are set up. They are Anodisation, Hot Process Treatment, Heat Treatment and Plating (see Figure 5-16)

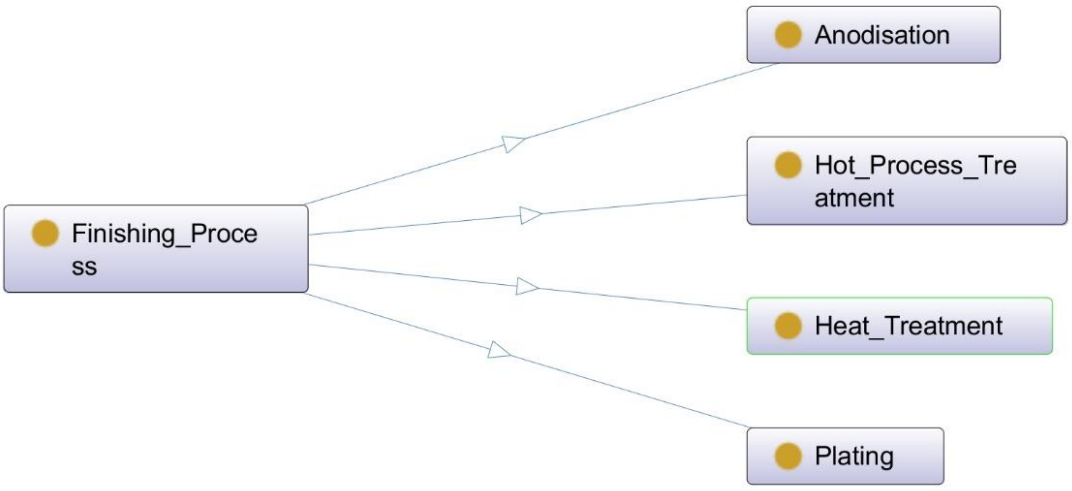


Figure 5-16 Finishing Process Classification

Based on the Methodology in Chapter 4, the production process component contains the most common processes and methods (see Figure 5-17). This case study focuses on Drilling, Polishing, Pressing to connect product component with production processes.

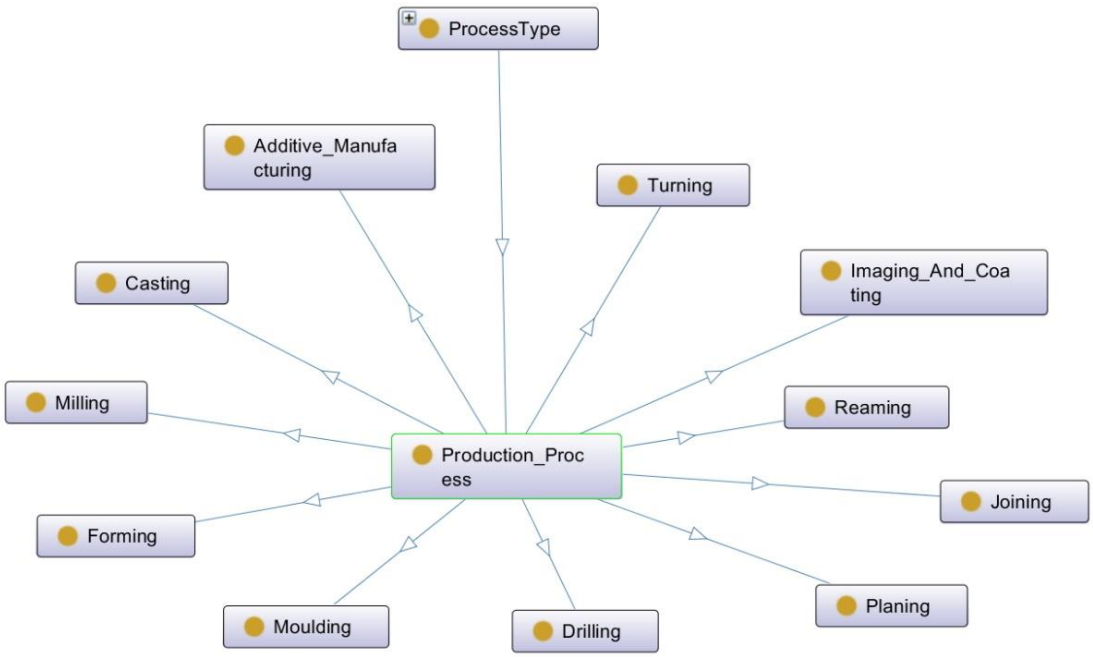


Figure 5-17 Production Process Ontology

5.4.4 Detailed Process Ontology design

Similarly, the Process Component has certain descriptions and it includes has_costComponent, has_resourceComponent, has_cycleTime, has_demo, has_position, has_activites, and has_sequences. Moreover, the Resource ontology is described by using has_type, has_capability has_logic, has_deliverytime, etc.

5.5 **Resource Ontology**

Resource ontology describes an available resource list that includes resource capability, process requirements for specific production system model. To enhance the relationship and reduce complexity, a process-based hierarchical structure of resource ontology is used to link with the Process ontology.

5.5.1 Resource Type

Based on the Process ontology, various resource classes are covered in the Resource ontology. The topology of resource can be classified as Production Units, Assembly Units, Material Holding Units, Delivery Systems, Production

Systems, Finishing System, Packaging Systems, and Support Systems (see Figure 5-18).

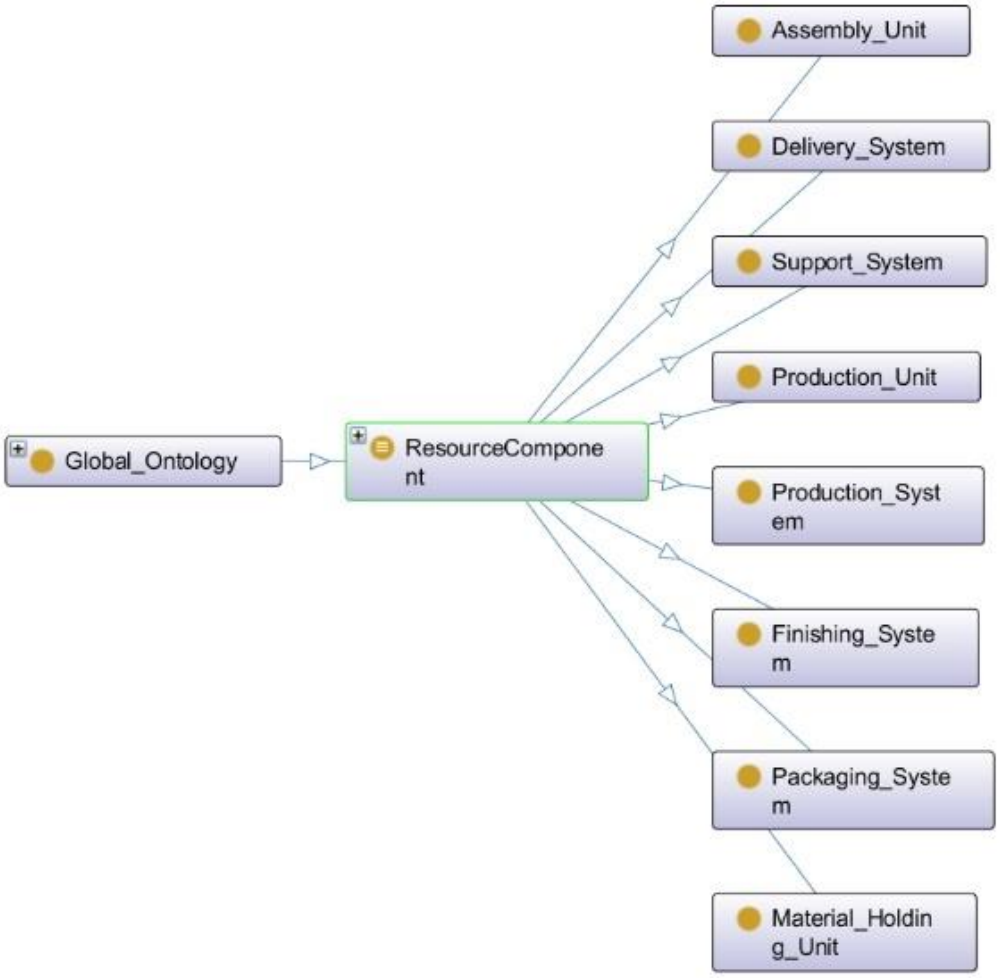


Figure 5-18 Resource Ontology Classification

5.5.2 Detailed Resource Ontology design

From the cardinality of relational ontologies, it is found that products, processes and resources are relatively dependent. Each database component is linked by a contact ontology, which can help to identify the required ontology. Figure 5-19 shows a detailed ontologies design for one of test cases.

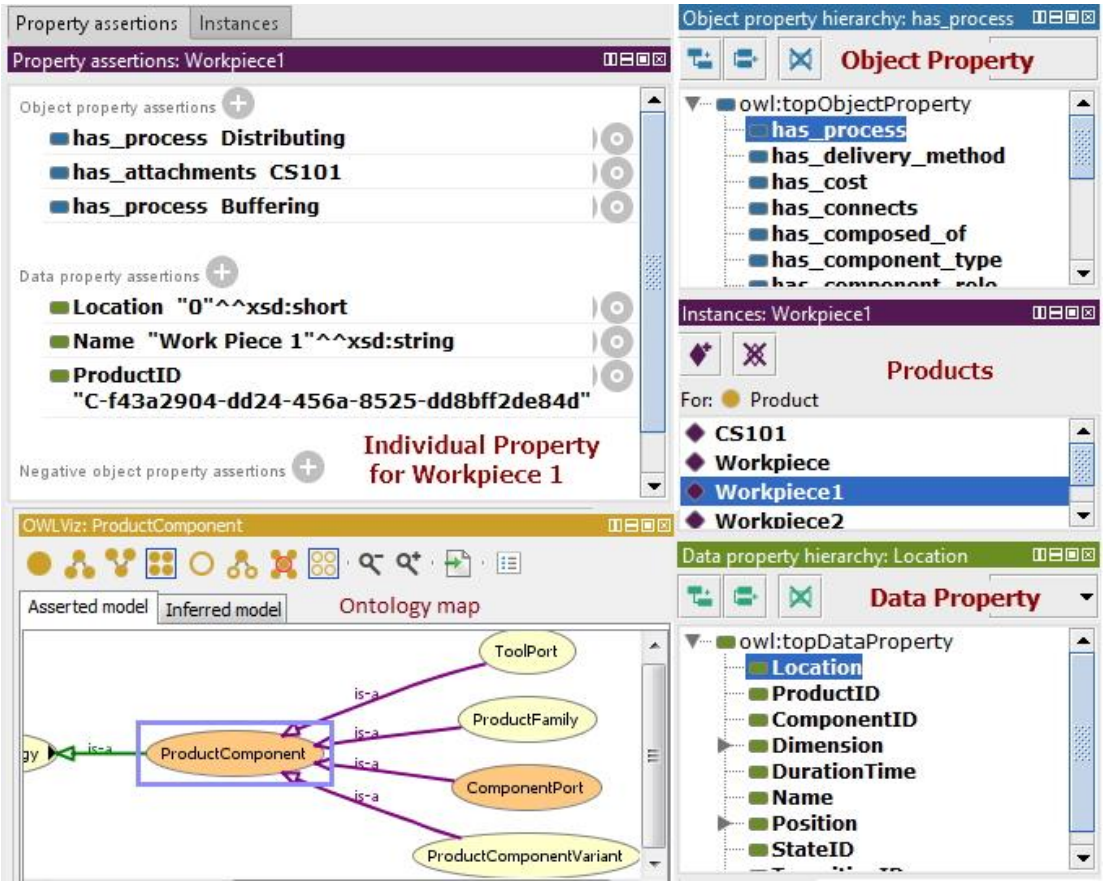


Figure 5-19 Product Ontology Instance for Festo Didactic Test Rig

The instance window, which at the right-middle part in Figure 5-19 shows all the instances of the Product ontology, such as CS101 as a metal attachment and a couple of work pieces. Figure 5-19 also displays the detailed object properties and data properties of PPRR ontologies, and the relationship between each component can be checked by OWL_Viz plug-in (showing on ontology map window).

5.6 Semantic Transformation

Real-time data processing and exchange can be based on advanced web technology and network support, such as data service. However, the semantic-based information exchange is still at a primary stage in the existing operating system and application layers. Thus, semantic web can extend web technology even further, which gives accurate information meaning in the different semantic contexts, and it is to enhance the computer and human interoperability. Machine readability improves the comprehensibility of

information and the accuracy of information dissemination. Machine-readable data describes resource metadata for retrieval, filtering, or human knowledge inheritance. Semantic Transformation includes document processing and ontology mapping (see Figure 5-20).

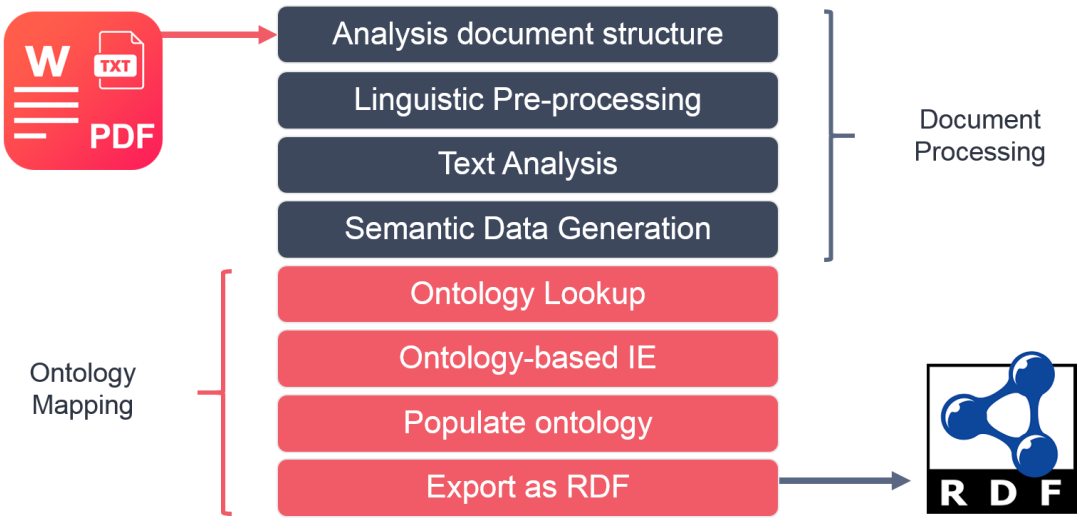


Figure 5-20 Semantic Transformation Processes (Maynard et al., 2016)

The object of semantic data is to translate data to the meaningful data so that semantic software can recognise and process intelligent query, knowledge representation and prediction. To understand the meaning behind data, semantic software needs to accurately understand the meaning of each word, sentence, and paragraph. Therefore, three basic things are to be considered in the semantic data: language, grammar, and query process. The detailed elements of representing semantic data on this case study will be described in the following sections.

Semantic language provides an automated translation method, and it gives the meaning to the data based on the ontology structure. Ontology structure is a pre-defined knowledge representation including concepts, semantic logic and some basic relationships. With the help of semantic language, ontology can be accurately identified, analysed and connected to a single domain or different domain of interests. The shared ontology will then be integrated into a robust ontology unit to support expansion and compatibility of projects. In order to achieve the conceptual reality, semantic programming includes

semantic analysis, meaning mapping and fuzzy query. The semantic dictionaries define the logic of the topic data, terminology as well as the rules, to automatically retrieve information and establish the relationship between each data and will be able to implement intelligent learning and expansion. An ontology is developed and uses semantic language with the following purposes:

- Reuse knowledge: reusing ontology to expand the previous version, achieve another similar ontology or solve another problem in different domain;
- Share knowledge: sharing information structure or semantic layout for other domain ontologies
- Simulate a domain: building a pre-designed ontology library and verifying the feasibility of the solution.

In this research, semantic technology is applied to retrieve information from product-process-resource XML files and is utilised each component of explicit PPRR data representation on the process simulation tool. Semantic language can enhance the automatic capture and identification of information including, but not limited to, text documents, tables, CAD files etc. Informal ontology structure obstructs reusing and sharing ontology, so ontology is usually encoded as a common format that software can understand and maintain easily. In this case study, Resource Description Framework (RDF) is a default ontology structure, which can be edited and described by GATE (semantic software).

5.7 Document Processing

5.7.1 Analysis of Document Structure

The Information resources in ontology typically mean the related documents in the same domain or project, such as text documents, CAD files or hardcopy. These documents describe ontology specific events, time and concerned resources. Current electronic documents for this case study are using XML format, which contains extensible product, process, and resource information.

Thus, standardised information modelling is necessary for establishing a unified and structured information exchange standard. In the industry, textual information is normally captured from the software export file, process planning table file, word documents, etc. This section will explain the document processing from unstructured XML files and then transform it into plaint text.

The pre-processing task is to automatically transform irregular structures into a machine-readable unified text structure by using the semantic analysis model. Through the analysis of unstructured XML tags, text information can be translated as elements, components, and attributes. Based on different component types, the components' properties will be assigned as a product, process, and resource. Additionally, the attributes also will be different for each component type. For example, the process component has States that contain Initial State, Time, Position, Transitions, etc. In order to improve the robustness of the semantic analysis model, the semantic analysis of XML tags is based on the text rather than XML parsing. Therefore, this model can also be applied to normal language text and structured data analyses.

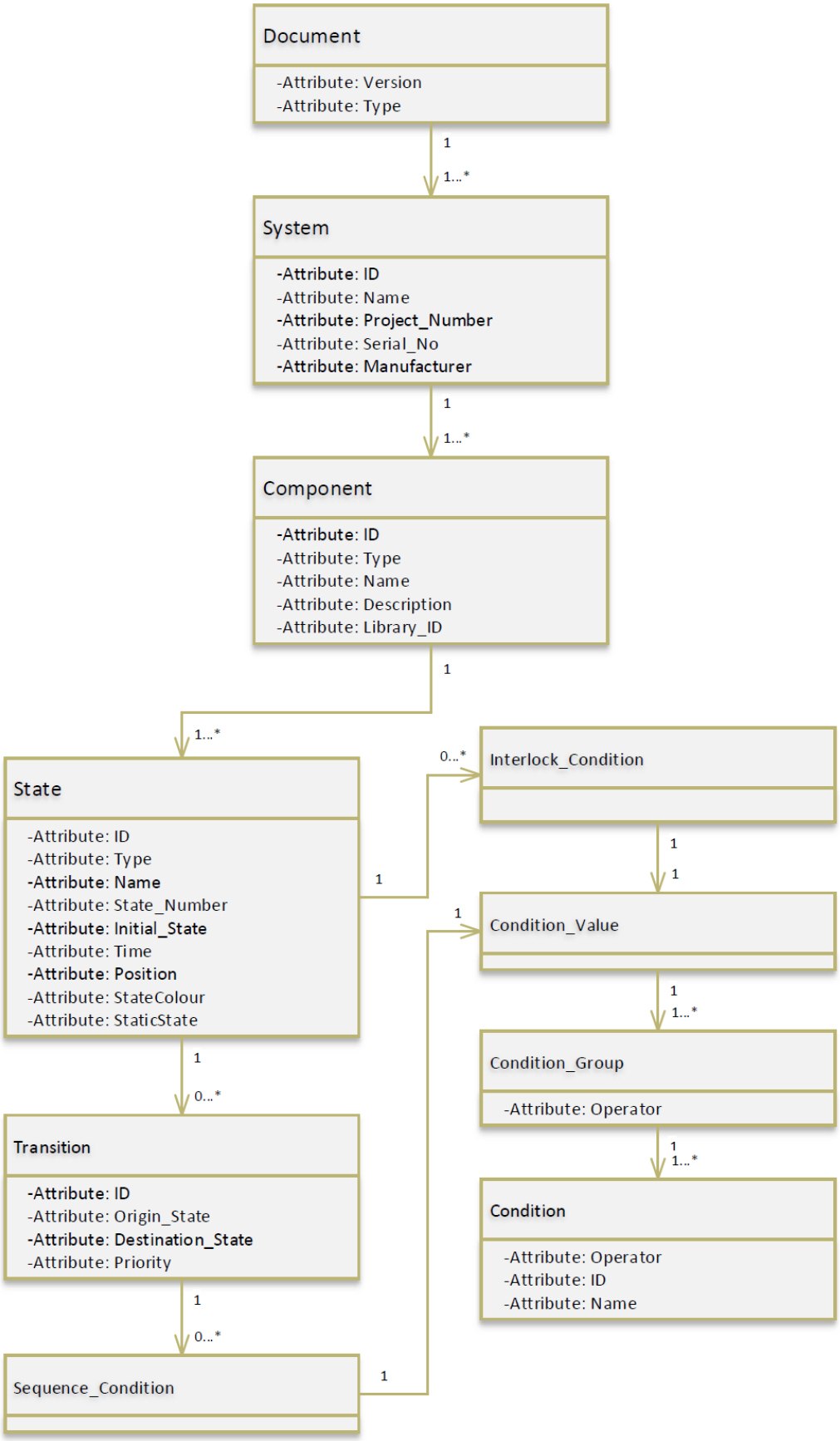


Figure 5-21 vueOne Processing Structure

The semantic analysis model has been developed for representing XML resources, which is showing in Figure 5-21. This model can help researchers and industry experts to retrieve, organise, and share structures without manual identification and misunderstanding.

5.7.2 Linguistic Pre-processing

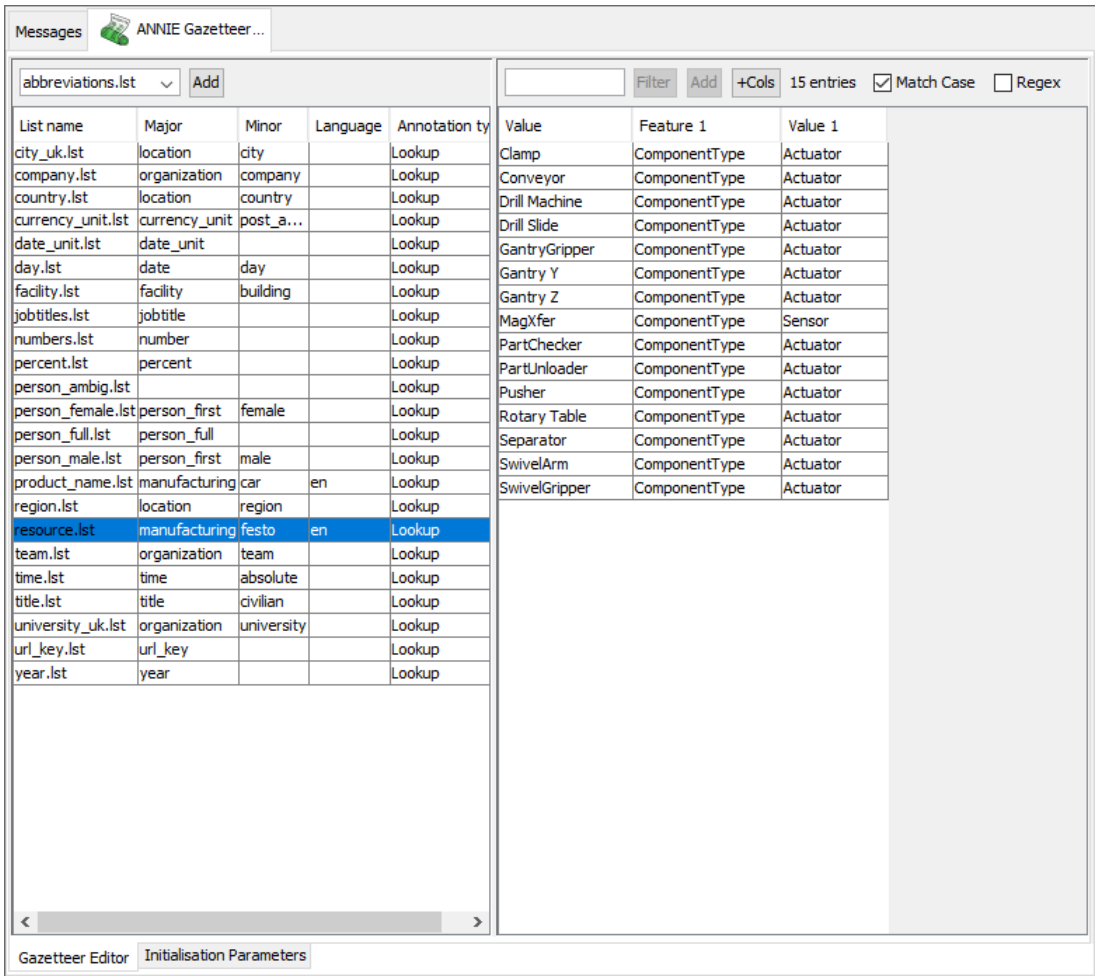
Documents represent a collection of systems and components and they are including product, process and resource. Assuming *S* is the system in a document, *S* will be split into several components after pre-processing. As an extensible mark-up language, customised labels can be presented in different formats or language to help humans-read. This increases the difficulty of automatic computer identification and classification. Thus, each label will be treated as a phrase or even a sentence. Syntactically, a sentence is composed of several words, which have the weakest semantic relationship, but the most easily identified and divided from documents. The Part-of-Speech (POS) of each word is the key to address syntactic and semantic meaning. In addition, POS is usually divided into eight parts, but industry documents can focus on five important speech elements, such as the noun, the pronoun, the verb, the preposition, and the conjunction. Therefore, automatically tagging POS and tagging related semantic tags are the first step in semantic analysis.

POS Tagging: In the natural language analysis, POS and text can be automatically tagged and prepared for higher-level analysis. Although POS tagging is not the first step of text analysis, it is still important in many scenarios like POS disambiguation, knowledge management, and sentence reconstruction. Rule-based POS tagging which is an automatic natural language analysis tool has been used in this case study. Automatic identification methods include probability method, statistical method, neural network method and Markov chain model. Due to availability and scalability, rule-based POS tagging method is the primary analysing method and can achieve the document analysis requirements.

S-P Structuring: The subject-predicate structure is the basic sentence of linguistics, and it has all the process descriptions based on this rule, such as

Pusher Move to Work, Conveyor Activated. Pusher as a Noun Phrase (NP) is the subject, and Move to Work as a Verb Phrase (VP) is a predicate. VP sometimes also includes other types of phrases (such as a place or state).

Gazetteer Identification: Gazetteer is a predefined customised term and phrase list contains a set of words with major category.



List name	Major	Minor	Language	Annotation ty
city_uk.lst	location	city		Lookup
company.lst	organization	company		Lookup
country.lst	location	country		Lookup
currency_unit.lst	currency_unit	post_a...		Lookup
date_unit.lst	date_unit			Lookup
day.lst	date	day		Lookup
facility.lst	facility	building		Lookup
jobtitles.lst	jobtitle			Lookup
numbers.lst	number			Lookup
percent.lst	percent			Lookup
person_ambig.lst				Lookup
person_female.lst	person_first	female		Lookup
person_full.lst	person_full			Lookup
person_male.lst	person_first	male		Lookup
product_name.lst	manufacturing	car	en	Lookup
region.lst	location	region		Lookup
resource.lst	manufacturing	festo	en	Lookup
team.lst	organization	team		Lookup
time.lst	time	absolute		Lookup
title.lst	title	civilian		Lookup
university_uk.lst	organization	university		Lookup
url_key.lst	url_key			Lookup
year.lst	year			Lookup

Value	Feature 1	Value 1
Clamp	ComponentType	Actuator
Conveyor	ComponentType	Actuator
Drill Machine	ComponentType	Actuator
Drill Slide	ComponentType	Actuator
GantryGripper	ComponentType	Actuator
Gantry Y	ComponentType	Actuator
Gantry Z	ComponentType	Actuator
MagXfer	ComponentType	Sensor
PartChecker	ComponentType	Actuator
PartUnloader	ComponentType	Actuator
Pusher	ComponentType	Actuator
Rotary Table	ComponentType	Actuator
Separator	ComponentType	Actuator
SwivelArm	ComponentType	Actuator
SwivelGripper	ComponentType	Actuator

Figure 5-22 Gazetteer Lookup Lists

Figure 5-22 demonstrates a gazetteer list of manufacturing system, and users can take it as a dictionary to describe each system or production line. Each gazetteer list includes major category, minor category, language, and annotation type. Majors are used to tagging phrases, such as location, date, product name. And Minor defines sub-category or list type. For example, Festo and car are the same major for manufacturing, but they are different gazetteer lists. Language property describes gazetteer's language. For the same list can

have more than one language to enhance system robustness. Annotation type can be searched in JAPE logic for annotation classification. The default annotation type is Lookup. Feature type and attribute value can explain each word's property or phrase for future ontology generation.

5.7.3 Text Analysis

After the previous processing, the current document has been classified into a set of phrases including most of the proper nouns and custom phrases. Before taking the next step, the existing documents are evaluated to ensure whether all contents are accurately identified. Then all the unrecognised phrases will be added as new words to the data dictionary or using manual adjustment to update special vocabulary in this case study.

Based on the existing dictionary, the document is classified into a set of pre-defined phrases. The next step is to mark each element with a certain tag by following the analysis rules. Those rules are defined for looking up the manufacturing process and identifying the relationship between each component in the document. The following rules are the first priority for developing analysis rules.

All nodes between two same tags belong to this tag, such as all process states. Processes are children of one component, and the states belong to the component.

The rules defined to recognise element are showing below:

System: It has a list of core components in a manufacturing document, excluding states that cannot build a direct connection with system level.

$$System ::= \{Component\}$$

Component: It includes all types of component with states including actuator, sensor, process, manikin and robot.

$$Component ::= \langle \text{Actuator}|\text{Sensor}|Process|Manikin|Robot\rangle\{State\}$$

State: It may contain ether static state or dynamic state with a number of transitions. But it does not include sequence condition, such that:

$$State ::= \langle StaticState | DynamicState \rangle \{Transition\}$$

Transition: It is a list of sequence condition, excluding interlock condition, i.e.

$$Transition ::= \{SequenceCondition\}$$

5.7.4 Semantic Data Generation

The current data is transported by using an XML file between different functions or software, and it is read through a fixed DOM reader module. To ensure that the meaning of the data am not be changed by semantic transforming tool, an evaluated ANNIE Gazetteer package will be imported into GATE based on DOM reader module in a virtual process planning and commissioning tool. The analysis results are represented as data with semantics (see Figure 5-23), and all the information of components then will be converted into semantic data by GATE, such as Destination Sate, Interlock and Conditions.

For example, *StateID* (marked as a blue colour in Figure 5-23) is defined as a state index, which signed as the identity of each process and the meaning of transition. It includes *TransitionID* (process sequence number), *Origin_State* (current state ID), and *Destination_State* (the following state ID). Also, it can decide the process flow in the current process. If the process order changes, a system only needs to modify the *Origin_State* and *Destination_State* according to the corresponding state ID. Furthermore, the state duration time and position could also be changed to a new value-based on process changes.

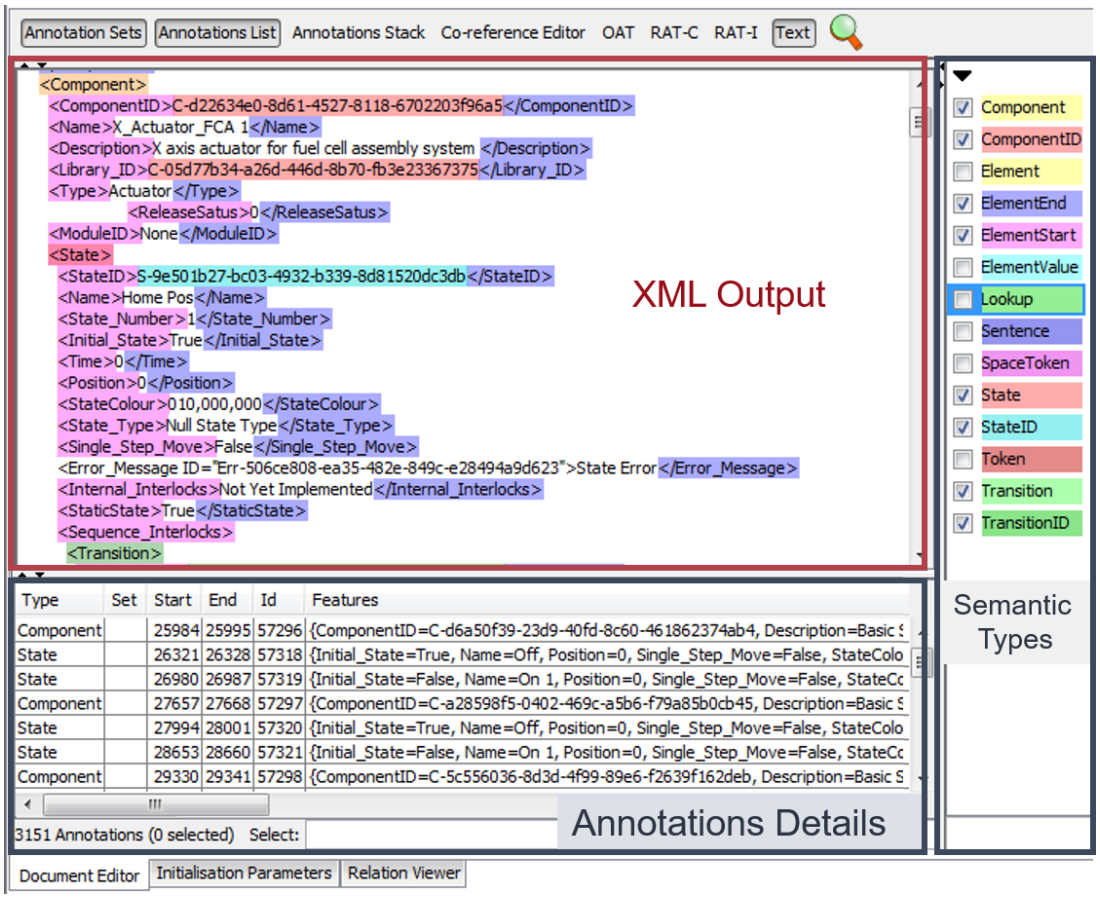


Figure 5-23 Semantic Data Translation

The ANNIE Gazetteer package is using UTF-8 encoding and hierarchical classification storage, so it is scalable and transplanted in different operating conditions or environments. The approach can be extended to support design changes in other similar manufacturing systems.

5.7.5 Mapping with Ontology Dictionary

Based on a pre-defined ontology structure, ontology instances are automatically generated from semantic data. Figure 5-24 shows the results of semantic data mapping with the ontology structure. Ontology dictionary has been used to structure and integrate data, so that product, process and resource information can be represented in a structured database and then smooth communication can be achieved between domain areas.

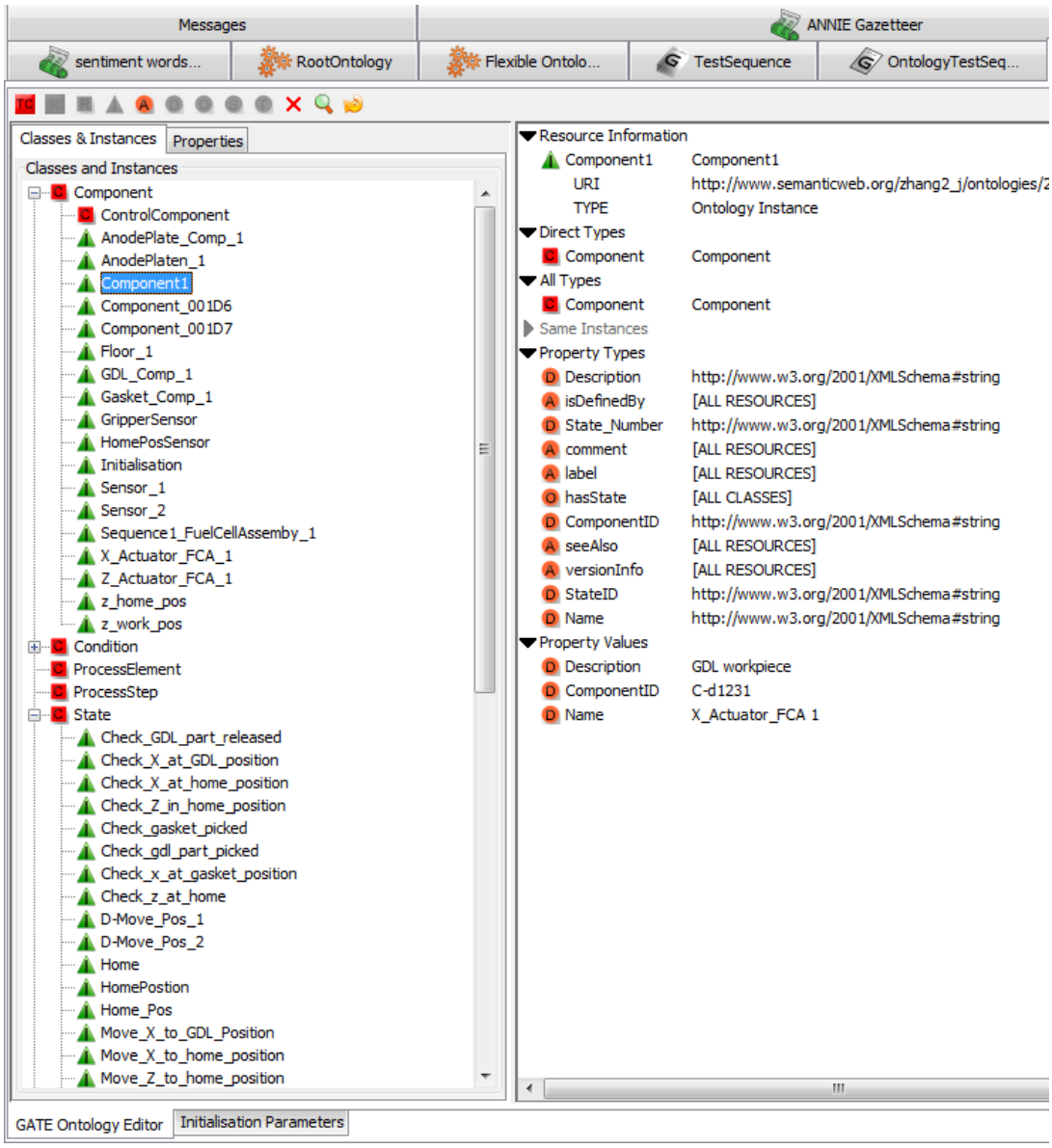


Figure 5-24 Product-Process-Resource-Requirement Ontology Mapping

OntoRoot gazetteer provides a link between ontology and GATE resources using dynamic gazetteer generation plugin. Using onto root plug-in, GATE could process text annotation with class URL, URL and type based on the existing ontologies. Moreover, the classic extract information in GATA uses a Java Annotation Patterns Engine (JAPE), which builds a grammar library via regular expression operators. So JAPE rules are created to recognise the related components and link ontologies with control logic document. The ontology mapping process is demonstrated in Figure 5-25.

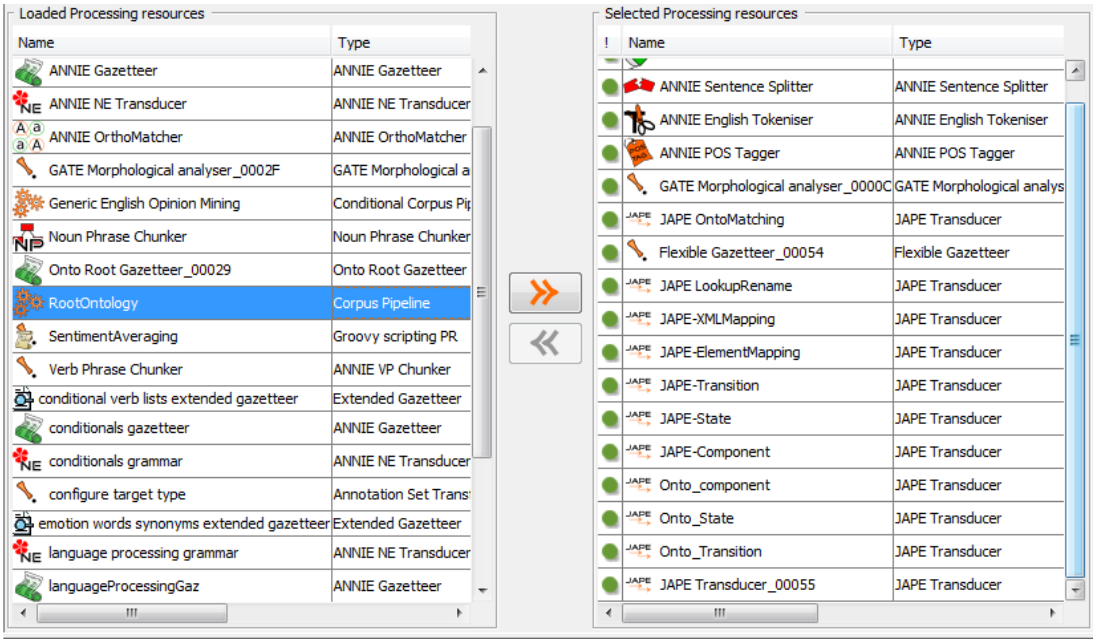


Figure 5-25 Ontology Mapping Processing

After ontologies and semantic data automatically matched, the pick and place station's variable data can be flexibly changed without data inconsistency. It means that process data is associated with product data and resource information like gripper movement, and it can be reconfigured according to battery dimension and plate size.

5.8 **Summary**

A Semantic-Ontology Engineering Framework (SOEF) has been implemented in this chapter. Ontology development covered high-level ontology relationship creation and low-level detailed PPRR ontologies design. To transform vueOne data, a natural language processing structure is introduced for linguistic pre-processing. System information in vueOne tool is mapping Product Ontology and component data are linked with related Process-Resource Ontologies. Based on the gazetteer lookup list, semantic engine classified process components and resource lists into different ontologies. After the previous processing, existing knowledge is recognised and marked up in a vueOne document. However, the engineer needs to evaluate unrecognised phrases for new knowledge generation. Furthermore, text analysis uses pre-defined rules to link Product, Process, Resource and Requirement ontologies together. A JAPE is used to create automation data

generation logic. Thus, Product-Process-Resource-Requirement ontologies can be automatically generated without any human action. In this research, the ontology editor tool is only used to display ontology data structure and instance details. Another novelty of this implementation is a reconfigurable automation ontology manipulation rules created by domain ontology API (Jena). User edits PPRR ontologies by using a recipe-based command-line method. New ontology data is directly processed by manipulation rules and a formatted XML file is able to import to vueOne tool for system evaluation or digital simulation.

CHAPTER 6 **Research Cases Studies**

6.1 **Introduction**

This chapter describes experiments via a couple of test case to evaluate the implementation of the Semantic-Ontology Engineering Framework (SOEF), which has been demonstrated in the previous chapters. The case studies are designed for didactic purpose, but the assembly systems are developed from real automation assembly lines. Each physical device is simple or small size of production line also known as Make-Like-Production (MLP) facility. In the following case studies, PPRR ontology structure is evaluated by SPARQL query using Protégé as ontology viewer. Moreover, semantic transformation and ontology manipulation provided a proof of concept for the contributions of SOEF.

6.2 **Festo Didactic Test Rig Assembly System**

To verify this new methodology of PPRR ontology integration, a Festo Didactic Test Rig was used in the first case study to define the basic manufacturing concepts and verify the modelling of ontology integration and semantic transformation. This chapter introduces the implementation of basic ontology design and data representations, which is also referring back to the previous chapters with the support of Festo Didactic Test Rig case study.

6.2.1 Case Study Overview

This case is based on a Festo Didactic Test Rig as Make-Like-Production (MLP) system and the goal of it is to present a smaller version of the realistic automation test system, by using the virtual simulation technology. It represents a real manufacturing process within the automotive industry, and it can bring some effective evaluation research concepts for improving the existing automotive technology. The Festo Didactic Test Rig is accomplished by integrating simulation modelling with experimental models, to simulate and optimise the entire process. Its aim also includes reducing production lifecycle as much as possible. The case study relates to a multi-category auto-parts production and processes, as well as resources that required achieving this

laboratory-based system. A number of changes are required to design car engine elements and these have an impact on any associated processes, resources and requirements. One of the major goals, therefore, is to integrate product design data with manufacturing system analysis and simulation, so that production line analysis can be done at an early design stage.

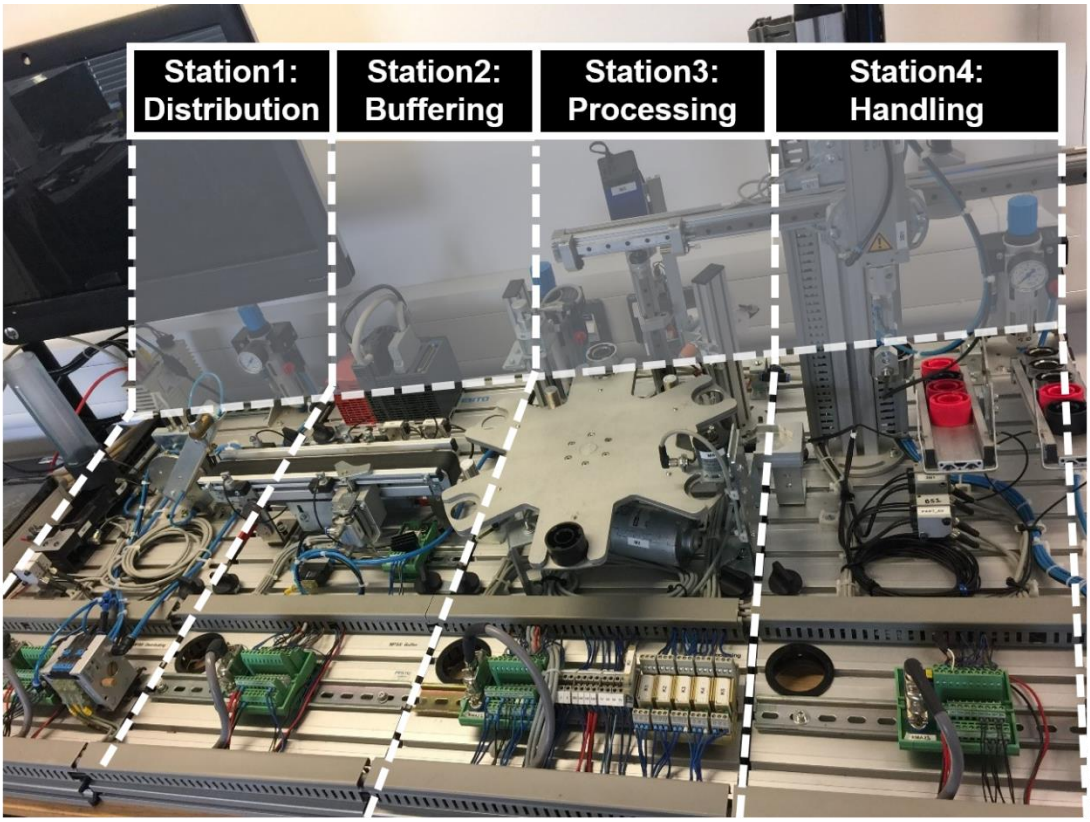


Figure 6-1 Festo Didactic Test Rig

Figure 6-1 presents the Festo Didactic Test Rig with four stations, which include Distributing (Station 1), Buffering (Station 2), Processing (Station 3) and Handling (Station 4) station. In order to translate this Test Rig to simulation, all components contain more than 300 CAD models and 35 processes for single cycle to be completed. The advantages of this 3D simulation are liberalisation of system communications, which could build up the connection with real PLC or soft PLC. At the very beginning, this Test Rig was developed for Siemens PLC and all control models are implemented to be suitable for Siemens logic. To extend the capability of the Festo MLP system, Automation System Group tries to use Mitsubishi PLC to replace the Siemens PLC. However, electronics engineers and mechanical engineers

need a complete model set to restore the whole processes. To be able to help physical system design, 3D simulation tool demonstrates each process with Siemens PLC and Mitsubishi PLC.

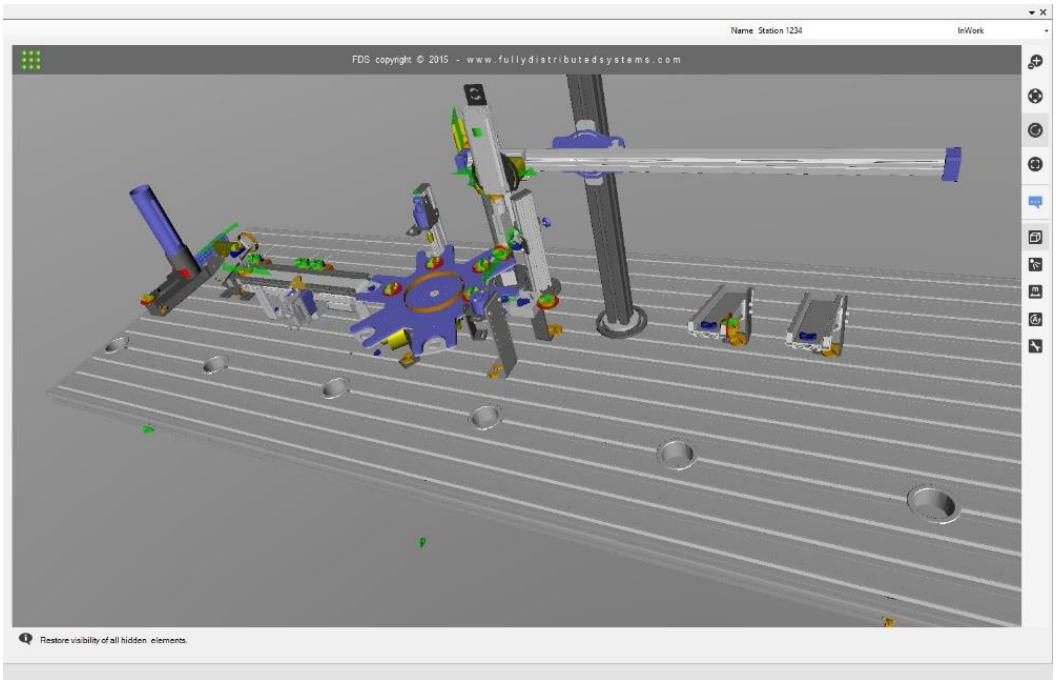


Figure 6-2 vueOne Simulation Models

Figure 6-2 shows the vueOne simulation environment and Figure 6-3 shows some selected components from the Test Rig, such as Pusher, Swivel Arm, Conveyor, and Separator. In this case, those components are used as the main components and a production system is created with all relevant processes and resources to simulate the whole production line during the product design stage. The Distributing station is used as the first ontology development and semantic design model. In this station, there are three actuators: Pusher, Swivel Arm, and Swivel Gripper. Work Pieces are inserted from the hopper and then delivered to the Buffering station via Pusher and Swivel Arm. These are taking control of work pieces movement. Moreover, sensor data are essential to process simulation under sequence conditions. And then while Pusher and Swivel Arm moving, interlock conditions between the components will be checked automatically.

The Buffering station controls the speed of the production line, and then to wait for an empty space at the Processing Station. Thus, conveyor and

separator are the main actuators in the Buffering station. To calculate production volume, three sensors are set in the conveyor which is showing with green round module in Figure 6-3. The most difficult part of this station is to process multiple parts at the same time, and with the signal of index table at the Processing Station. If cycle time is delayed at an index table or due to the processes changes, then the separator will be affected and changes the related process.

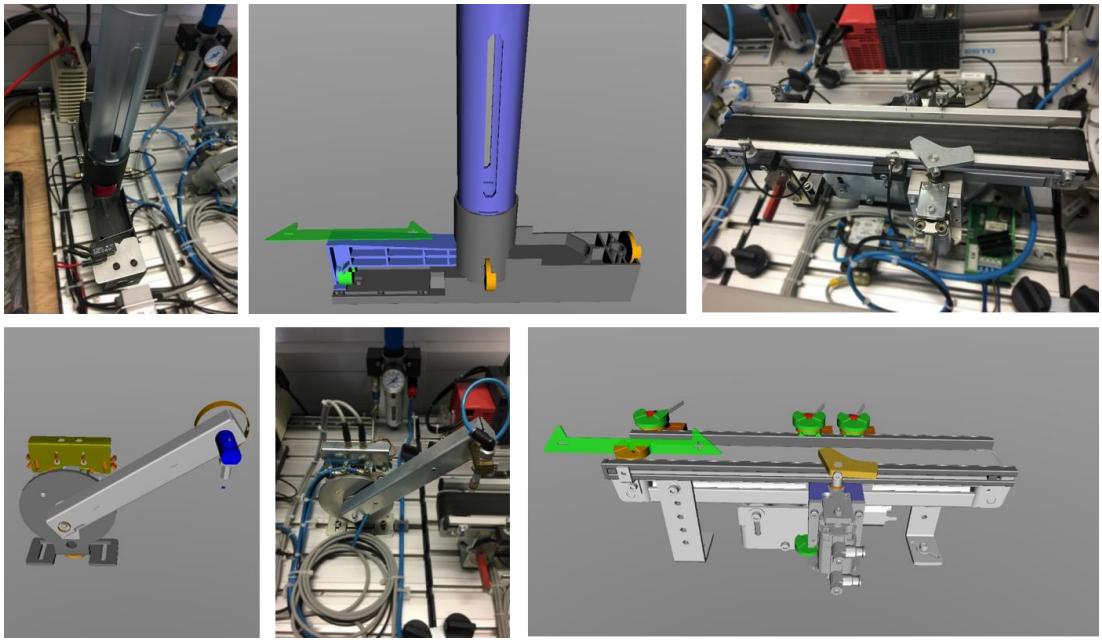


Figure 6-3 Festo Components for Distributing, Buffering Stations

In this case study, an integrated product, process, resource and requirement ontologies were used to support decision making, for the product design, and to predict requirement changes if product design changes. All data and the structure of ontologies were changed based on different requirements, such as actuators' cycle time, high volume processes, and process costs. The main aim of this case study is to create a well suitable and extendable ontology structure for the automation system process, to test the capability of ontology integration with traditional manufacturing 3D simulation process. Moreover, the evaluation section will focus on SPARQL query evaluation and product-process-resource-requirement ontology validation.

6.2.2 Case Evaluation

The case study has selected Work Piece 1 (Workpiece1) and Work Piece 2 (Workpiece2) as examples. In order to show the detail design of product ontology. From the cardinality of ontologies, object property and relational data property, the Workpiece1 has established the relationship with process and other related parts. Individual property viewer shows the data property of Workpiece1 (*has_name*, *has_productID* and *has_location*) and also Object Property (*has_process* and *has_attachments*). The link between product and process is built by *has_process* property, and the example has presented that Workpiece1 has two processes (Distributing and Buffering). According to the definition of Process Component, a process has cost component and cycle time property. Hence, a designer could get the result of total cost and cycle time via a search query called SPARQL query for Protégé ontology editor.

6.2.3 SPARQL Query

According to the integration methods and modelling rules, the ontologies has established for manufacturing system design and set up the connections between Product, Process and Resource. Based on the existing ontologies and linked database, the target of the query example is to find related product IDs for certain process. In this test case, Swivel_Arm_to_Work is used to locate Station2 as a process contact instance. Because of the relationship between process contact ontology and product ontology, Workpiece1 and Workpiece2 are found (see results on Figure 6-4).

Furthermore, the two query restrictions are Process_ID (?Process asg:process_id ?Process_ID . FILTER(?Process_ID = 7)) and Product_Volume (?Product asg:product_volume ?Volume . FILTER (?Volume > 0)). The related products produce by Swivel_Arm_to_Work and their volume is more than zero.

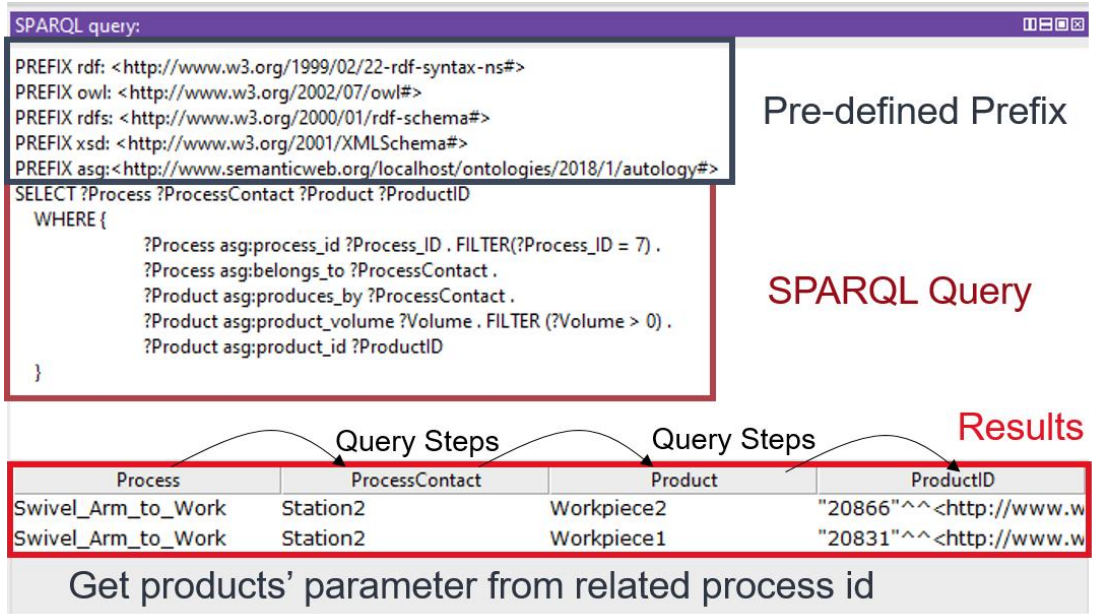
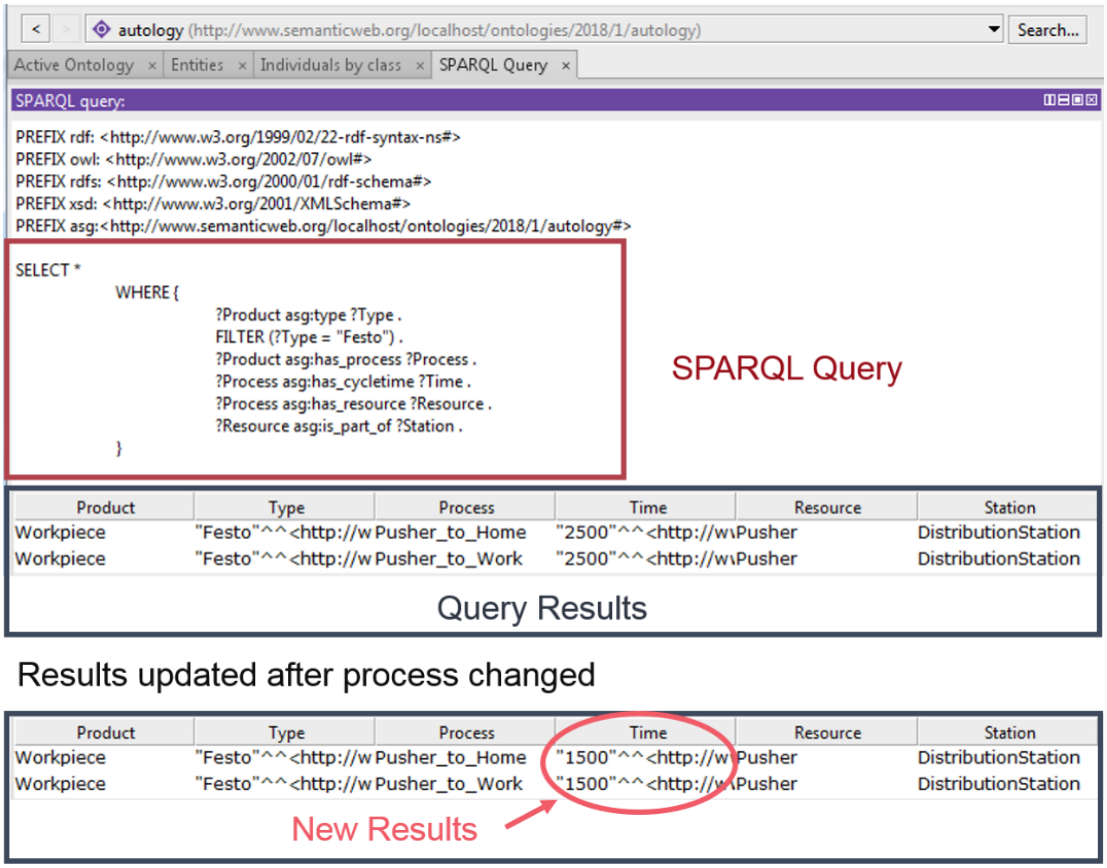


Figure 6-4 Process Query for Case Study

Figure 6-4 also shows the query results which were searched using the ontologies and mapping with the databases. Process Contact ontology builds a link between Process ontology and Product ontology. Therefore, a user can find any product that uses any specific process.

6.2.4 PPRR Validation

The main purpose of the query is to evaluate reliability and validity of the integration of product (P), process (P), resource (R) and Requirements (R) data and predict the future process performance at early design stages, so series of process performance changing are expected to find by searching a process from current ontologies, such as cycle time and total cost. Before starting a query, the Global_Ontology was defined by "PREFIX asg: <#ontology Path from location computer#>" and related queries body and the class files are also referenced in the query.



Results updated after process changed

Figure 6-5 SPARQL Query and Results

According to the integration methods and modelling rules, a SPARQL query has established as shown in Figure 6-5. Through the query, product component, cycle time, and total cost are showed in query results windows with ontology style to practice semantic query. After modifying pusher processes, the cycle time and total cost are recalculated by Protégé reasoner. Therefore, this case study could find any product that uses any specific process with detailed process changes. In other words, process changes can be predicted during product design processes.

6.2.5 Create New Process

This test case demonstrated a semantic recognition for customer requests and process modification based on new process description. In this case, work piece needs to drill a hole on top of the product. Figure 6-6 shows the command-line interface for Festo processes modification.

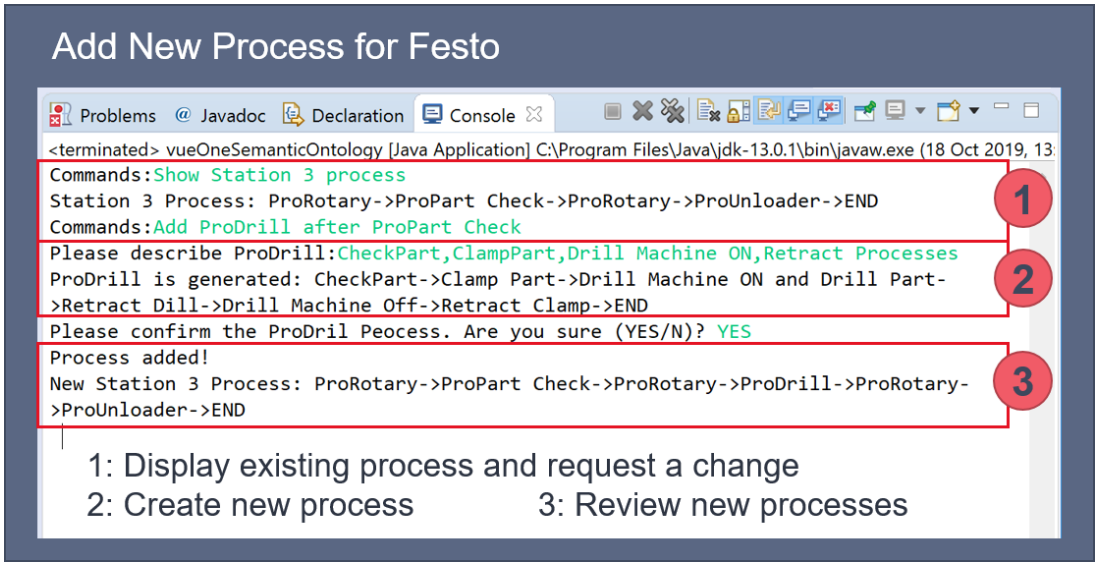


Figure 6-6 Command Line Interface for Adding Festo Processes

The first step reviews existing processes for Station 3 by using semantic query and requests a ProDrill process after ProPart Check process based on previous query result. The second step asks user to describe the ProDrill process. In this step, description is processed by semantic engine to find correct detail processes to avoid process duplication. The ProDrill is auto-generated with retract processes. After user confirmation, new Station 3 processes is displayed for custom evaluation.

6.2.6 Case Study Concluding Remarks

Festo Didactic Test Rig has demonstrated the capability and usability of proposed PPRR ontology. This methodology has been evaluated via SPARQL search query and amend queries in this chapter. End-user can search related process steps based on the link (Contact ontology) with a certain product. Process parameters can change by the simple user interface and all modifications are immediately reflected into product and resource ontology. Furthermore, a knowledge-based ontology integrated process planning and product design at the system level to ensure knowledge consistency. However, the data generated for this case study is still using traditional data import methods and transformation tools. The automatic data transformation method is achieved by the Apache Jena based semantic engine which is demonstrated in the next chapter. Despite user interface development are big

challenges for this research, a simple command-line user interface is implemented for end-users who do not familiar with ontology environment and tools.

6.3 **Battery Cell Assembly System**

To evaluate PPRR ontology with semantic technology, a battery cell assembly system was used in the second case study to extend the manufacturing concepts and verify the modelling of automatic semantic transformation and process prediction. This chapter introduces the implementation of semantic mapping ontology and system integration, and some information covered in the previous chapters will be the support of Battery Cell Assembly System case study.

6.3.1 Case Study Overview

Battery pack design and manufacturing for Electric Vehicles (EVs) is diverse and quite complex, due to the growing requirements and rapid technological changes, such as different cell packaging and battery module assembly for different applications and battery chemistry, etc. As a result, few different battery pack designs are expected to be on a single assembly line, in order to address the changing requirements. The assembly lines are also requiring a massive reconfiguration and redesign over a short period of time. For example, it is known that the BMW i3 battery assembly line went through some major changes three times in the past few years. Under such circumstances, a rapid reconfigurable assembly system design approach can provide an opportunity of addressing automatic readjustments of the assembly line for different products, and it is including new product variant analysis, assembly line evaluation and assembly system reconfiguration, etc.

This case study in this chapter is based on a Make-Like-Production (MLP) battery assembly line installed at WMG. This MLP facility aims to mock-up basic battery assembly processes in order to configure, integrate, test and evaluate current automation systems, and to address reconfigurable assembly system design for the frequent changing product, process, resource and requirements. This assembly line is composed of many automatic and

manual assembly stations, which can automatic guided vehicle to the components delivery and production monitoring system.

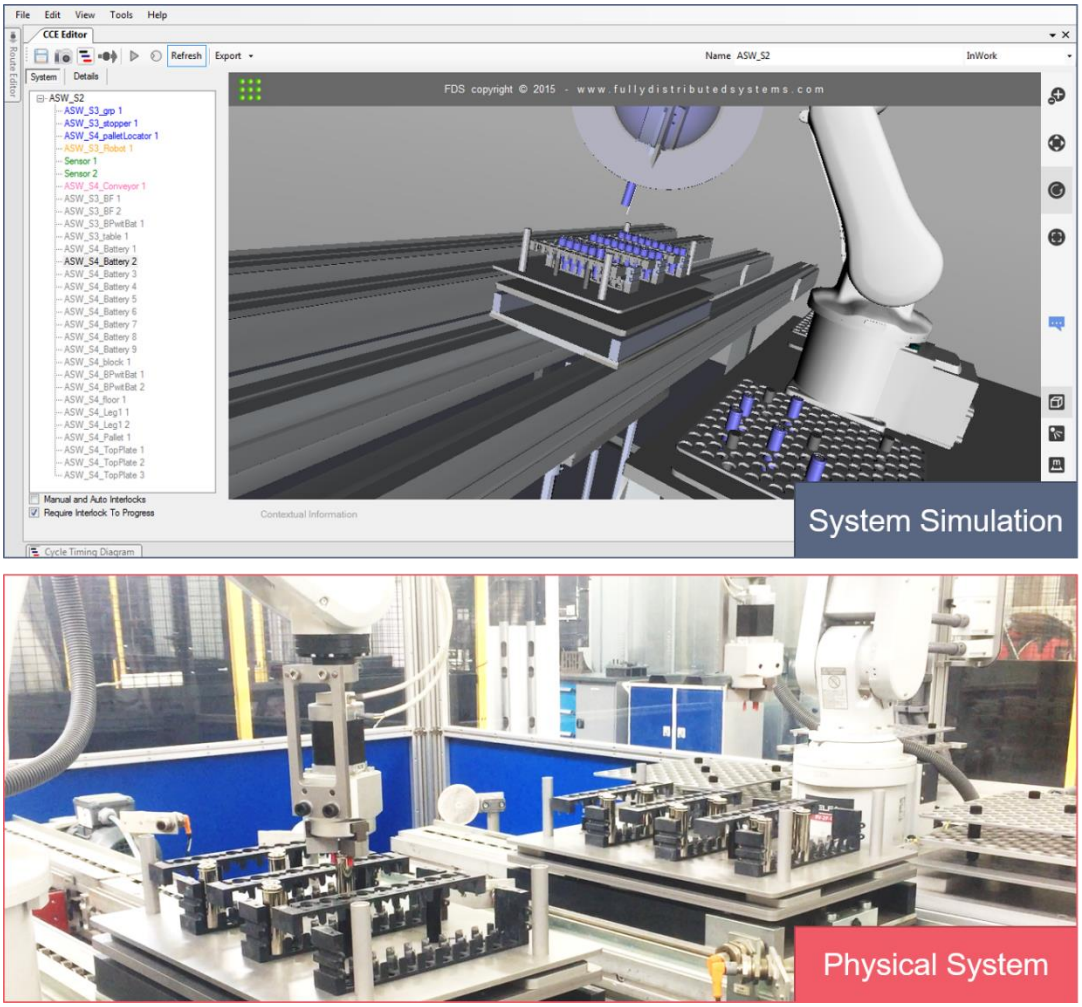


Figure 6-7 Pick and Place Station of the MLP Facility

The MLP battery assembly line was structured for different product categories, so a pick and place system has been designed to ensure the system is efficient, scalable and reconfigurable (see Figure 6-7). A number of modelling and simulation tools, therefore, also have been applied to test and evaluate different operating conditions and product requirements, which to reduce the time and engineering costs. However, the existing modelling tools all would require experienced engineers to complete each simulator revision. Hence, the focus of this case study is to reduce human efforts by using an ontology-based semantic model of such system design revisions and consequently reduce time and engineering costs.

In this case study, the bespoke pick and place station of the MLP battery assembly line has been selected to carry out the top plate assembly, and it used a gripper to pick-up and drop-down battery cell plates. In this station, there are four sequence checks to determine the location as well as to control processes. So the condition of each sequence check is a core step of the operation sequence (known as Process). An ontology-based on semantic model is used to transfer XML file, which is an output of simulation system, into semantic data and then map the basic rules for system prediction, generated by vueOne simulation toolset.

6.3.2 Basic Rules for Prediction Model

Battery plate can be changed for different battery dimensions. For example, the original plate focuses on battery 18650 (Diameter: 18.4 mm), but a new battery's diameter is 22.4 mm (see Figure 6-8). Battery assembly station (Station 3) is developed for picking and place single battery cell to battery plate. However, the new battery dimension causes a new plate layout and robot programming. To update the robot place position, a new process planning requests to test robot programming.

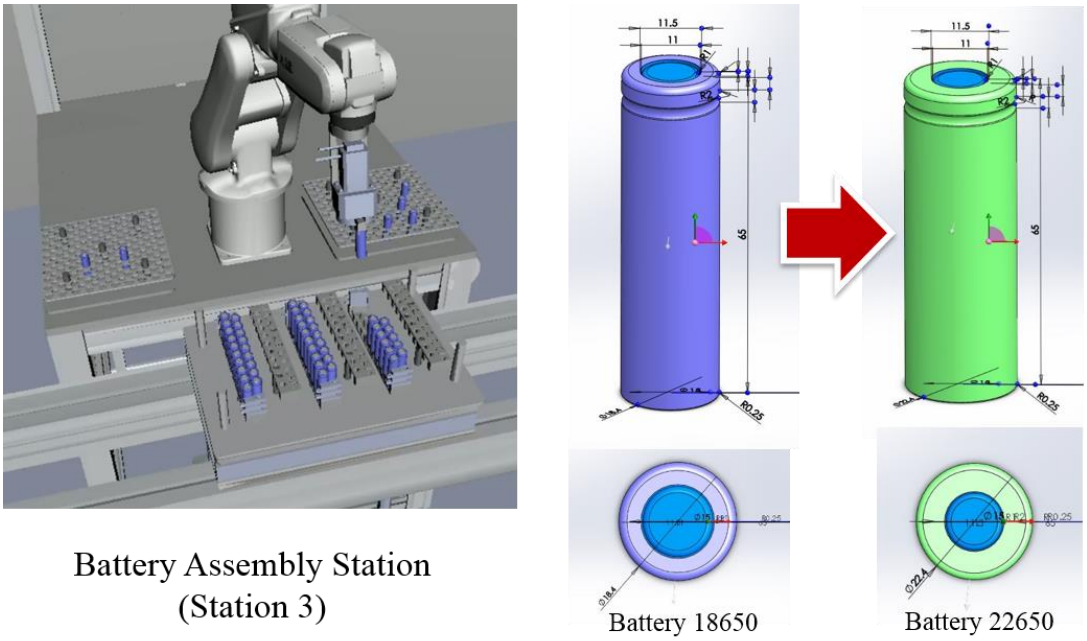


Figure 6-8 Battery Assembly Station (Left) and Different Battery Types (Right)

Current prediction model can calculate each battery's location and automatically generate or modify the operation file (XML) sequence. Figure 6-9 introduces the algorithm logic including product, process, resource and requirements changes. In addition, Figure 6-10 is an example of battery layout arrangement algorithm and the ontology modification is developed by Jena API.

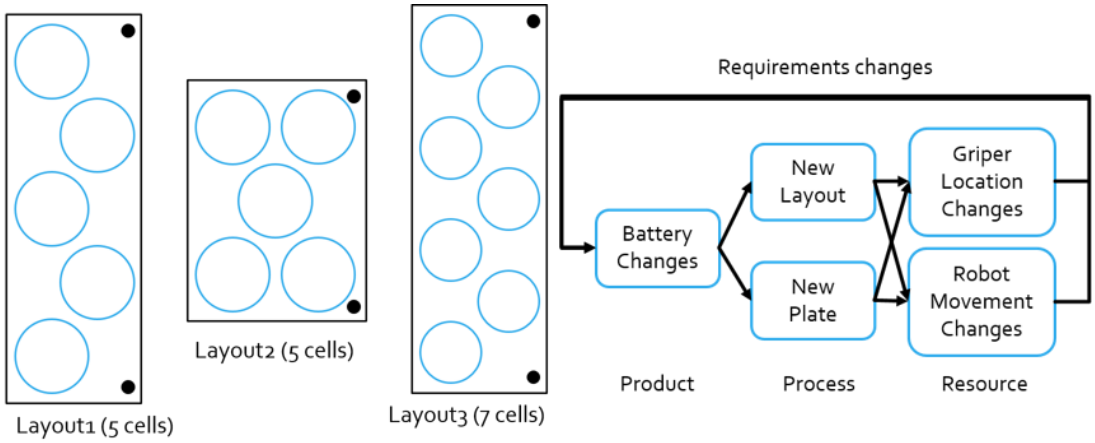


Figure 6-9 Prediction Model Algorithm Logic

Battery Position Modification by Jena API

```
String batteryIndex = InputHelper.getInput("Enter a index of Battery:");
State state = getStateByName("D-Move Pos 3");
String newposition = batteryLayoutArrangement(battery, batteryIndex);
Boolean success = State.updateStateParameter("Position", newposition);
if (success) {
    System.out.print("State-" + state.Id +"  " +"Name: "+ state.Name+"  ");
    System.out.println("New position: "+ state.Position);
}
TransformerFactory transformerFactory = TransformerFactory.newInstance();
Transformer transformer = transformerFactory.newTransformer();
DOMSource source = new DOMSource(doc);
StreamResult result = new StreamResult(f);
transformer.transform(source, result);
System.out.println("Done");
```

Figure 6-10 Algorithm Example of Battery Layout Arrangement

Battery dimension changes may affect cell layout or plate dimension design. For any new dimensions, the batteryLayoutArrangement can calculate a new

cell centre point for specific battery cell index, and then provide a new position for the griper movement position (D-Mover Pos 3).

Therefore, the existing layout and positioning for each resource were set for an initial state. And horizontal and vertical arrangement rule, battery dimension, gripper location link, and cycle time calculation model are configured to update new parameters for simulation XML file.

Automatic Process Sequence Changes

```
//1: Read Width, Height, Diameter of targeted battery as W, H, D from user;
//2: Get "D-Move Pos" state as State1 from battery_cells.owl file;
//3: Repeat the steps until last step in State1
        Calculate battery size and center point using W, H, D;
        If new battery size fits cell pannel Then
                Change State1.Step.Position to new battery center point;
//4: Print out all changes for owl file;
//5: Update owl file via semantic model;
//6: Convert new owl file to XML file for simulation tool;
```

Figure 6-11 XML Data Update Algorithm

From the example algorithm shown in Figure 6-11, the system was able to calculate correctly the coordinates for each cell and update related positions. In addition, other parameters within XML file can also be modified and updated according to the new requirements. While the simulation model within the virtual engineering environment (i.e. vueOne) can also be updated and validated based on the new design concept.

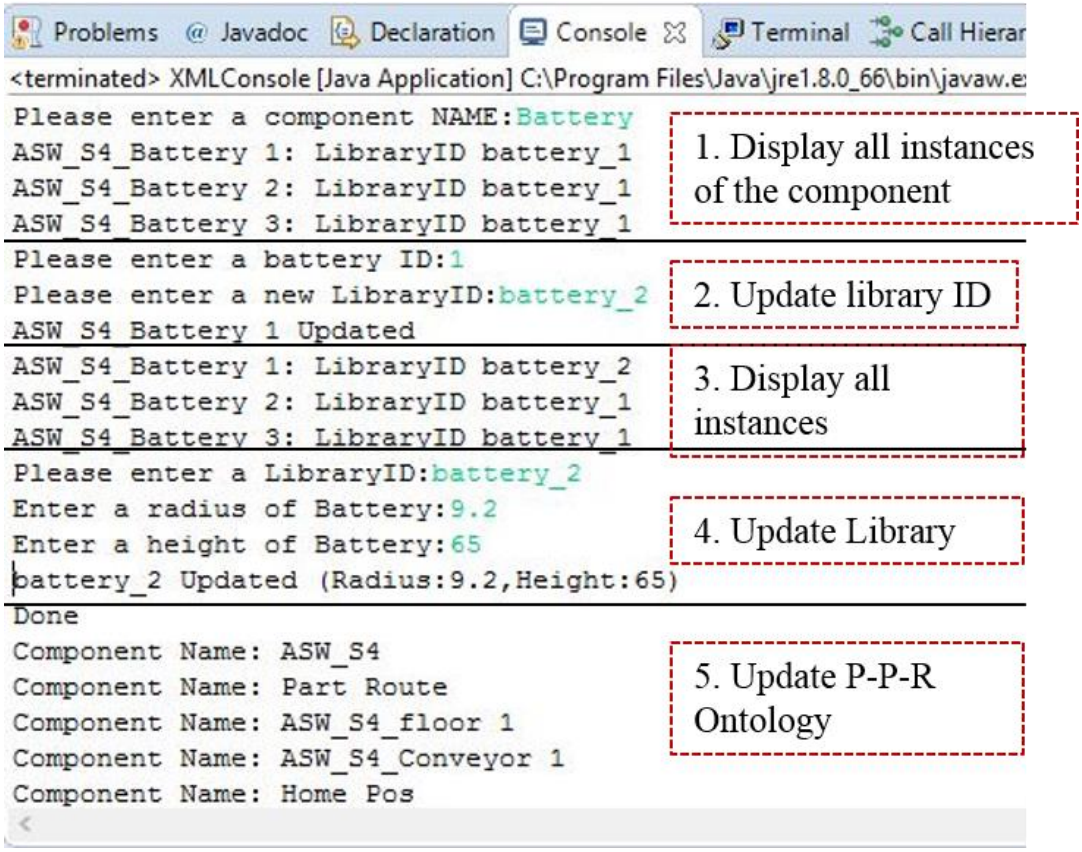


Figure 6-12 User Interface of Battery Ontology Updating

The user interface for updating the battery process is showing in Figure 6-12. The first step is finding all instances of the target component. User can select certain *library* from the list of instances. The second step is updating battery *LibraryID* via a pre-defined battery model. In this case, *battery_1* is replaced by *battery_2* for *ASW_S4_Battery 1*. After evaluating all instances, the user should insert the new battery dimension following dimension rules. The final step is the automatic process for ontology updating. User could review all related component for new assembly processes.

6.3.3 Case Study Concluding Remarks

Information reuse and knowledge generation are not easy to achieve for visual engineering. To collaborate with different domain engineers, maintain data in a synchronous way is necessary to enhance efficiency and keep high accuracy. In this research, a semantic-ontology methodology translate engineering data to semantic content to preserve manufacturing information

during data exchange. Semantic technology, ontology structure, and rule-based reasoning are used to improve manufacturing data sharing and reuse.

This chapter has shown how semantic transformation tools automatically generate ontology data with semantic content. Apache Jena based library is used to develop ontology manipulation functions with a CLI for end users. The battery cell assembly system is used to test the rule-based model. The case study has successfully demonstrated process changes when battery dimension modifications and plate layout prediction for different battery model. In order to evaluate the proposed semantic methodology and to enhance this work in another manufacturing scenario, all data changes vueOne simulate tool in this research.

6.4 Summary

This chapter has evaluated two case studies with a couple of test cases to assess the Semantic-Ontology Engineering Framework (SOEF). Both case studies are proof of PPRR ontology integration in information searching and ontology modification. The Requirement Ontology created an extendable relationship with Product, Process and Resource Ontology to link domain ontologies in different test cases. Due to product requirements changes, new drilling process sequences were added in Process Ontology. Furthermore, process speed and destination are optimised for robot path planning. The various semantic transformations are applied to document processing, auto ontology generation and customer query analysis.

Framework Requirements	Test Cases
1 Integrated approach using VFF, SuFSeF and TOGAF framework to reuse existing knowledge	A couple of advantages have been involved in the test cases including crossing-life cycles, data repository and requirements-driven reuse model.
2 Definition of relationships for product, process, resource and requirements to support existing database's structure in the Data Link Layer	The PPRR ontology has been defined to create a database-ontology link during implementation of the SOEF.
3 Semantic Transformation Model developed for automation document processing, auto ontology generation and natural language analysis in the Function Layer	Documents are translated into automation knowledge in test cases and custom product requests are recognised for certain tasks using semantic transformation Model.
4 Ontology Mapping with new and existing knowledge in the Function Layer	Semantic data are auto-generated to ontology instance to link with the PPRR ontology for reusing knowledge across the various case studies.
5 Modification of PPRR ontology based on new requirements in the Data Link Layer	Process sequence changes are triggered by new product requirements. SOEF has enabled to add, edit and delete ontologies based on PPRR relationships.
6 Handling customer request for searching and editing in the Presentation Layer	A CLI is implemented to support customer request for ontology manipulation and system simulation file generation.

Figure 6-13 Achievements of the Test Cases on the Framework Requirements

SOEF has enabled the semantic implementation in the case studies to recognise natural language and reuse the PPRR ontology model. Figure 6-13 summaries the achievements of the test cases to fulfil the framework requirements of SOEF.

The first case study has demonstrated the capability and usability of integration PPRR ontologies for "Workpiece" (Product),

“Pusher_to_Home/Pusher_to_Work/Drilling” (Process), “Pusher/Drilling Machine” (Resource) and “Add 6mm Hole on Workpiece” (Requirement). Test case 1 has evaluated the relationship between “Swivel Arm to Work” with “Workpiece1 & Workpiece 2” via a process contact ontology. In addition, Test cases 2 and 3 have focused on the changes of “Pusher Cycletime” and “Machining Hole on Workpiece” to validate requirement-driven reuse model during crossing-life cycles. Meanwhile, natural language processing has demonstrated in the first case study with a command-line user interface (CLI).

The battery cell assembly case has presented knowledge reuse capability for reconfigurable automation assembly system. Based on the existing assembly process and battery cell information, semantic transformation model converts system simulation file to semantic information and auto-generate PPRR ontologies. In battery assembly station 3, battery 18650 is changed to battery 22650 within 5 steps using Java-based ontology model. Furthermore, battery (Product) changes affect “Griper Gaps” (Process) and “Robot Movement” (Resource). Thus, “Griper Open/ Close” and “Battery Location” are modified by pre-defined rules. Finally, battery library is replaced with new parameters in “ASW_S4_Battery *”, including radius and height.

The rule-based Semantic-Ontology Engineering Framework (SOEF) achieved semantic mapping with automation documentation and PPRR ontologies to support system simulation maintenance. In the various case studies, the semantic transformation model is verified in automation document processing, auto ontology generation and natural language analysis. Moreover, this chapter has demonstrated the importance of PPRR ontologies implementation for knowledge extraction and reuse. The significance of combine semantic and ontology technologies have been approved in satisfying this research.

CHAPTER 7 **Conclusion and Further Work**

7.1 **Introduction**

There are still some gaps between knowledge representations and reconfigurable manufacturing tools of reusing existing semantic and ontological data. Hence, two research questions have been summarised. First, how can a reconfigurable manufacturing system integrate product, process and resource knowledge to decrease the required skills and design time in order to launch new products? Second, can product design data be transferred from various domain-specific software to a collaborative and intelligent platform to capture and reuse design knowledge? Furthermore, the author wants to understand the relationship between knowledge representation and real manufacturing tools. To solve these research questions, the defined objectives (see Section 1.5) have been examined in this thesis.

In summary, Object (1) is to understand current manufacturing status and identify the knowledge gaps. Based on the gaps, Object (2) and (3) are to contribute existing research using a novel research methodology. To evaluate the methodology, Object (4) is to validate PPRR ontology via two case studies.

7.2 **Review of Research Gaps**

Based on Object (1), the author has reviewed process planning method (Section 1.2.1), system simulation requirements (Section 1.2.2), virtual engineering environment (Section 1.2.3), and system integration challenges (Section 1.2.4). To meet the requirements for each manufacturing process, intelligent data models need to support and formalise the integration of heterogeneous life cycle data, and to enable the manufacturing systems performance prediction at an early stage of the design cycle. Additionally, the existing digital modelling tools are too complex to use, as they require a wide range of technical skills and manual work.

Ontology as a popular knowledge representation methodology has been reviewed from definition and classification in Chapter 2. In addition, it

concludes that ontology-based systems are suitable for rapid updating of the knowledge system. However, current design tools cannot be used to predict possible process changes and resource availability at the early product development stages. Moreover, data transformation cannot integrate semantic data in the current tools. Chapter 3 has reviewed data representation methods and semantic technology. There are three key data integration models including VFF, SuFSeF, and TOGAF. However, process planning and appropriate resource selection with product changes are not solved in those models. Furthermore, data representations are identified and integrated through ontology experts, which are limited by knowledge and understanding of a particular domain.

In conclusion, the knowledge gaps are founded in the literature review as follows:

(1) Rule-based Assembly Flow Design: There is a need for a systematic rule set to automatically help product designers, and it will be benefit by manufacturing and assembly knowledge to enable agile systems development with increased efficiency.

(2) Information Processing and Prediction: Current design system cannot fast turnaround with the adjusted demands and predict process changes at the product design early stages.

(3) Dynamic Information Analysis based on PLC Simulation Information: Visual simulation model clones real manufacturing system. Thus a dynamic information analysis model is requested to adjust process cycle time and report system performance.

(4) Sensor Data Integration: Due to the amount and irregular nature of sensor data integration, data processing and data mining pose tremendous challenges for data analysers

(5) Manufacturing System Data Integration: The semantic knowledge should be applied to multiple product lifecycle for implementing knowledge-to-application conversions

(6) Semantic Technology Implementation: To achieve product design and industrial manufacturing semantic integration, specific formalism(s) of knowledge representation should be defined and development by semantic analyst.

Data manipulation challenges currently exist from both the academic and manufacturing industry perspectives. Firstly, data collection from the software in use in industry is not easy and collected data will typically have different data formats. Secondly, from an academic perspective, a common data integration model is missing for automation systems integration. Thirdly, data cleaning and processing is application specific. The definitions of industry data are different in each case, so there is a requirement for a semantic transform model. Hence, existing knowledge cannot be reused for future information extraction. Finally, data modification is only focused on particular components and it therefore requires an experienced engineer to evaluate the results. Current ontology technology structures components with pre-defined relationships and as a result the academic area is only using ontology technology for querying items rather than ontology modification.

7.3 **Research Contributions**

In this research, a novel ontology-based semantic model has been proposed to improve manufacturing systems performance. By applying semantic technologies and decision-trees modelling, users can more accurately find the required product properties. At the same time, it has the advance semantic-web and visualisation to save cost and improve teamwork.

7.3.1 PPRR Ontologies Integration

This research has studied the processes and common tools of product design. It shows that based on product, process and resource ontologies, virtual factory systems integration can be achieved. The review indicates that the existing knowledge-based systems do not fully meet the current demands of manufacturing systems integration as well as the interoperability. The objective is to build a model in order to integrate different manufacturing systems together and re-use previous knowledge for future design.

The initial results have shown that after adding semantic modelling and connection tables it has strengthened the PPRR method. Product systems can match with corresponding process ontology and resource systems can be arranged to meet the process requirements. Separate connection tables provide the support of quick responses to queries, especially when a system needs to handle huge amount of data. Thus, it leads to the fact that collaborative development will enhance the digital lifecycle management and reduce the product development cycle.

7.3.2 Semantic Model

An ANNE Gazetteer with semantic engine has been built to transfer XML data to a computer-readable data (semantic data). Also, by applying semantic data and rule-based prediction algorithms, the developed system is able to predict changes in the system design on the basis of changes along with the product design and requirements. Furthermore, the integration GATE and Protégé software have enabled the semantic model to automatically match vueOne data with PPRR ontologies via semantic technology.

The semantic model provides an opportunity of creating a knowledge system to enable automation systems' reconfigurations and this model also provides an evaluation of the existing automation systems through knowledge-based approach. The PPRR ontologies development and semantic model rapidly improve the design time and reduce the need for specialised skills, to reconfigure and analyse manufacturing systems.

Product design, process plan and resources management play important roles in the rapid manufacturing system design's reconfiguration. If designers' queries can be classified and split, then more available product's models and components will be reused, modified and updated via the semantic-ontology methodology. Additionally, product solutions can be identified at an earlier stage, as designers will be able to check available assembly plans and resources with the help of semantic technologies.

7.4 Further Work

Future work includes the completion of overall system design, user interface, predictive algorithms and detailed manufacturing ontologies. Moreover, the design decision-making module will be implemented as an effective tool for the next generation of manufacturing systems integration. Real manufacturing system based various use cases will also be tested for the system feasibility and user experiences. To enhance the research objectives, the semantic methodology will be improved and implemented on the use cases.

In the future, the approach will be extended to include a selection of appropriate manufacturing resource components and optimising their configuration to match with product suitability and requirements. Also, Product-Process-Resource-Requirement (PPRR) ontologies will be embedded into vueOne system with a friendly user interface for improving system performance, and the semantic model will be created in an independent semantic engine with a flexible, scalable gazetteer library to enhance software portability. Moreover, PPRR ontologies will be combined with other different manufacturing ontologies, to create a standard semantic model of reconfigurable manufacturing systems.

The following plans are outlined for the next research stage:

- To integrate different databases using semantic technology
- To create a semantic model for databases integration between different manufacturing systems
- To improve current PPRR ontologies and create rules for ontology communication
- To build a friendly user interface for ontology system
- To create a simple semantic predictive algorithms for decision making
- To verify and validate the methodology with factory layout design case

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